INTERNATIONAL HELLENIC UNIVERSITY

Analysis of Greek Electricity System and evaluation of the impact of the flexibility options for future energy scenarios

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SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Systems

APRIL 2018

THESSALONIKI – GREECE

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Abstract

This dissertation was written as part of my MSc in Energy Systems at the International Hellenic University. The primary goal of the present study is to adapt and further develop an energy system model according to the Greek boundary conditions; a model al-ready applied by the Institute of Environmental Technology and Energy Economics in Hamburg. What is more, this master thesis includes theoretical research on mathematical optimization, as well as all the necessary data for the simulation subsequently presented. What is more, the issue is addressed and analyzed with the appropriate mathematical functions. The central part of the thesis is the development of the algorithm and the analysis of the power system. Eventually, an assessment of three scenarios of the author's choice is carried out.

Great emphasis is placed on the minimization of power system cost under technical and environmental constraints with a better integration of Renewable Energy Sources in the Greek Electricity System.

Alexandros Maronidis

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Alexandros Maronidis

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1 Introduction

A regional or national power system consists of power plants, transmission and distribution systems, monitoring and control devices. For such power systems short-, medium- and long-term system planning is required: 1. Short term power system planning usually plans the operation of power plants and the T&D equipment on hours or day-ahead basis. This is an ongoing day-to-day task in each utility. 2. Medium-term power system planning, usually plans which power plants are available in cold and warm reserves (inter-annual or seasonal planning). 3. Long-term power system planning defines which longer-term investments have to be considered in the power system:

Power system scheduling or master planning considers the demand side (consumers), the supply side (power plants), the link between these two and the electric energy transportation (transmission and distribution system)

Over recent years, the adequate integration of Renewable Energy Sources based power plants into such power system planning models became of increasing importance. Particularly due to the fluctuating character of most of the renewable energy options (mainly wind and solar sources), the interdependencies between T&D and power supply development become more and more complicated.

In the present thesis, we shall elaborate on the use of long-term power system planning and the construction of an optimization model, taking into consideration the electric supply aspect, based on an algorithm developed in TUHH. The optimization model is developed with Microsoft Excel 2016.

1.1 Motivation

Since the beginning of the 19th century and the initiation of massive changes in the industry, the rapid technological progress and population growth raised the need for energy demand to a great extent. This phenomenon is still present today and will be in the future too. The developing and developed nations should be able to face the problems that will arise in their energy systems (according to the constant rise of energy demand) regardless of their potential and their level [1].

A firm energy system certainly plays an integral role in each country's evolution in all possible aspects of life. This concern should be a continuous area of study due to the particular features it is comprised of. The concerns and uncertainties that prevail due to the financial conjectures of the latest financial crisis, deem necessary the expansion of the energy systems in the least cost way. At the same time, the growing power generation also comes with some drawbacks that the liable countries ought to deal with. CO2 emissions have resulted in energy production, depending on the fuel. The following graph demonstrates the emission coming from tons of main fossil fuels that were used for electricity production and their development through the years.

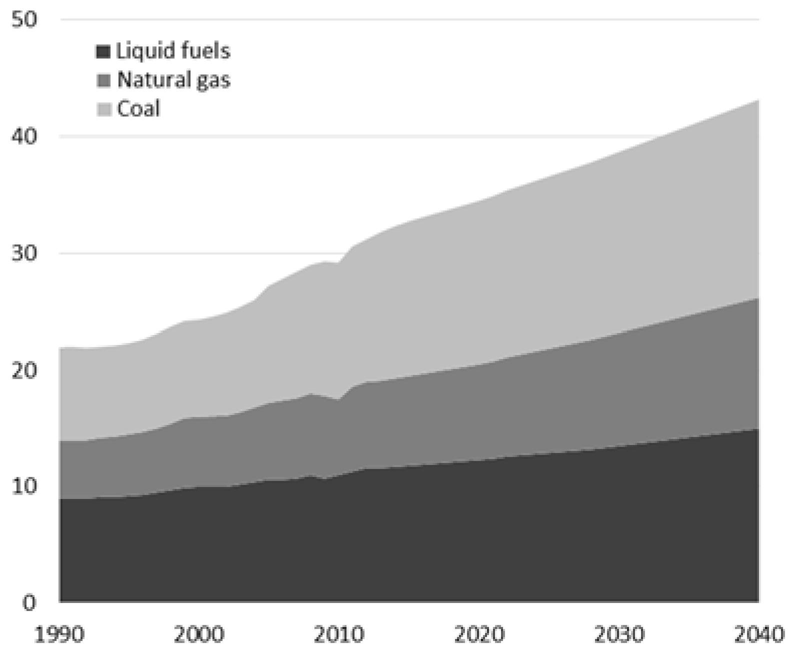


Figure 1.1: World energy-related CO2 emissions by fuel, 1990-2040 (billion tons per year) [1]

Evidently, the previous decade's coal and liquid fuels, which played a dominant role in energy production, emitted approximately 20-30 billion tons of CO2. The long-term forecast indicates an increasing tendency in the emissions field, that being the number one worrying factor for the environment. Greece, as a member of the EU and as a country that participates in the Kyoto Protocol, has imposed policies for the elimination of CO2 emissions and has published a study (which will be discussed further on) concerning energy production, while simultaneously reducing emissions.

The figure above reveals the need to shift from a fossil fuel economy to the green sustain economy of RES. The rise in the percentage of integration of RES in energy systems is now a one-way process. The technological potentials lying in this direction and the economic impact (energy costs and the amount of investment required) of such a transformation could function as a solution to the above-mentioned problems but still, a general study of the energy system is required.

1.2 Purposes & objectives of the thesis

The purpose of the present thesis is the long-term power planning of the Greek Electricity System with a least-cost approach to the expansion of the system. The requirements to be met are the increasing demand and its specific characteristics, as well as the implementation of technological improvements in the field of energy production. The basic technologies that will be implemented, owe their existence to the rising of new technologies of RES, upon which the emphasis will be placed according to the plans of the Greek authorities.

This specific plan has a time frame of 25 years. For the development of the expansion plan, Microsoft Excel 2016 and the VBA tool were used for the simulation of the process. Because the least cost expansion plan was developed primarily for Greece, it was considered that justified simplifications and assumptions covered for the possible lack of entry data. According to the latest report of IPTO of Greece (ADMIE), the increase in the demand of electric energy should be considered inevitable due to the population and household growth, as well as the evolution of the interconnections of the connected and the non-connected transmission system (Crete, Cyclades etc.) [2]. The comprehensive examination of the current situation of the system, and also the implementation of the scenarios according to EU and country policies, was concluded in an optimal solution.

2 Methodology

The second chapter illustrates the main pillars of the optimization problems and their operations for the master planning of power systems. It demonstrates the workflow, including all the necessary elements required to solve the particular problem. After a brief description of the existing knowledge, the planning operation of power system optimization is presented, while being at the same time an assessment method for the optimization of a model with various parameters.

2.1 Basics of Mathematical Optimization

Rockafellar (2007) defines optimization as an operation that tries to maximize or minimize a function analytically, relative to data that represents a width of acceptable solutions in a specific situation based on mathematics and computer science. This function leads to different solutions with the option to choose the best result (optimal result - an assessment which is influenced by different parameters). Also, there are many cases where the results are extracted from numerical methods without the need to perform analytical calculations [3].

The categorization of a problem (in the present situation an optimization problem) deals with the characterization of the model. One model can be characterized as discrete or continuous. That depends on the values that variables take, from a discrete set, as a subset of integers or variables which can take any real value. One other significant distinction is related to the existence or the absence of constraints in the model and therefore to the variables. Constraints can be simple boundaries, equalities or inequalities which connect the complex relationships among the variables [4].

An optimization model can also be single or multi-objective. The differences between them lie in the number of objective functions and the definition of the additional criteria to extract a more accurate determination of the desired degree of objective functions. Furthermore, the level of data or the nature of the model can be of deterministic or of stochastic nature. In the deterministic models, the parameters are known accurately whereas, a factor of uncertainty characterizes stochastic models [4].

2.1.1 Mathematical Formulation and Linear Optimization

The mathematical optimization is a process of mathematical formulation and the solution of the optimization problem. The solutions take the values of the solution space which is usually symbolized with the Greek capital letter $\Phi = \mathbb{R}^n$. The next thing is the objective function. The real valued objective function is a function of *n* unknown variables, and it takes values from the region [5]. In mathematics that is symbolized as:

$$f : \Phi \to \mathbb{R}^n, \chi = (\chi_1, \chi_2 \cdots \chi_n) \to f(\chi) \ (2.1)$$

Every combination of x variables is characterized as a possible solution to the problem. In every mathematical optimization, constraints exist that can be equalities or inequalities. Usually, the values satisfy the constraints limits. In the case that this does not happen we are presented with a so-called ‘‘non-feasible solution’’ which is not used as a solution to the problem. Constraints usually have the following form (2.2) [6].

$$g(x) \begin{Bmatrix} \geq \\ = \\ \leq \end{Bmatrix} 0 \left(2.2\right)$$

After this necessary separation, we define as maximization problem the problem which tries to solve the problem by finding the optimal solution (max.) (2.3). The feasible solution to this problem is every feasible solution which maximizes the objective function (2.4)

$$maximum\{ f(x) \mid x \in \Phi \} \quad (2.3)$$

$$\chi^* \in \Phi : f(\chi^*) \geq f(x) \forall x \in \Phi \ (2.4)$$

The reverse procedure occurs during minimization problems (2.5, 2.6). In general, a minimization problem is the opposite of a maximization problem [6]. Hence, it is common presented in the form of (2.7)

$$minimum\{f(x) \mid x \in \Phi\} \quad (2.5)$$

$$\chi^* \in \Phi : f(\chi^*) \leq f(x) \forall x \in \Phi \quad (2.6)$$

$$\min(f(x)) = \max(f(-x)) \quad (2.7)$$

This formulation leads to one of the most critical characterizations of the nature of the mathematical formulation, the *linear* or *non-linear optimization*. Linear optimization is characterized by the linearity of all objective functions and constraints. For a linear optimization problem we need to fulfill three requirements [6]:

1. The linear optimization problem must have maximization form
2. All the constraints must be equalities or inequalities with non-negative constant terms at the right place of functions
3. All the variables must be non-negative

In the case that all these requirements are fulfilled, we can proceed to the next step which is the numerical solution, via a computer program. For such a solution, the use of matrixes is necessary. The form of the function will be the equation (2.8).

$$z = \max(f(x)) = C^T x \quad (2.8)$$

In that equation z is the objective function of maximization of the function $f(x)=C^T$ is the scalar product of two vectors and x is the variable of our concern. The constraints of the above equation should have the form of (2.9), (2.10).

$$A \bullet x \leq b \quad (2.9)$$

$$A_{eq} \bullet x \leq b_{eq} \quad (2.10)$$

Where A is the matrixes, x is the decision variable vector, and b's are vectors form equations and inequations that contains the characteristics of all constraints [7].

2.1.2 Solving Methods

The two principal methods of linear optimization solutions are Simplex Algorithm and the Interior Point Method. The simplex algorithm will be used in this thesis to give a solution to the optimization task.

Simplex algorithm

In many problems in linear programming, more than two decision variables are required, meaning that different optimization techniques are necessary in order to find the optimal solution. Simplex Method is the typical method for solving linear programs with such characteristics. Usually, simplex algorithm is used to solve mid-term and long-term problems via two different approaches. The first is the foresight method and the second is the time-step method. The differences between them are represented in figure 2.1.

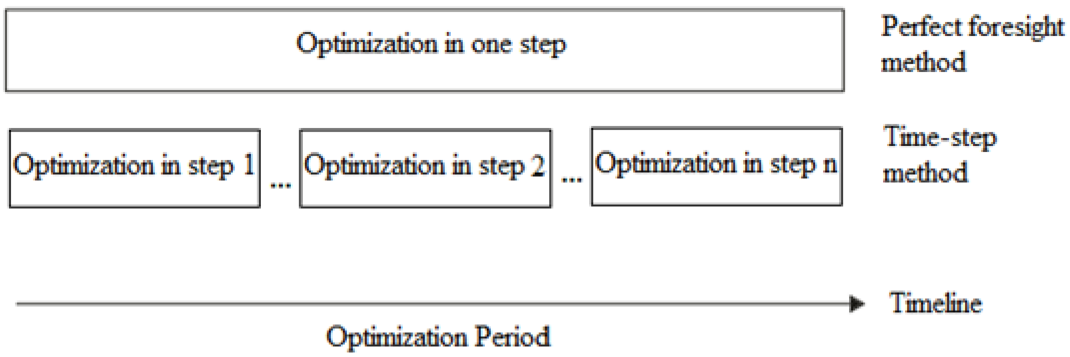


Figure 2.1.1: Differences between perfect foresight and time-step method [8]

The optimization steps of these two methods are illustrated in figure 2.1. In the perfect foresight method, time is considered as a whole factor of optimization in the system. The orientation takes place with the purpose of optimizing the cost (reducing the cost of the power system), and to positively contribute in the profit balance at the end of the forecast (which is based on an intertemporal basis), under a predictable future with specific information. That could cause an increase in the short-term costs, but for long-term motivation, different scenarios of optimization could be investigated, and sensitivity analyses could be carried out. [7]

The second method is the time-step method. In many cases, it is described as a Static Expectation Strategy. The primary focus of this method is the study of the model only in current boundary conditions, hence the term Static. The nature of the method is analyzed, merely as the cost optimization of the specific period that will determine the starting values of the following time-step, without a change in the parameters of the system. That makes this method useful for different nature energy problems but, not for the long-term planning of a system model [7].

The selection between the implementation of one of these methods comes from the fact of unexpected changes occuring in the model usually caused by the transition of periods. In the first method, the confrontation provides constant adaptation reaction in the whole time scale in contrast to the time step method which occurs in one period. All the previous claims, lead to the use of the time-step method as a tool for this long-term power system expansion and give the opportunity of correction in the case of sudden changes and unexpected results. [9]

2.2 Optimization & Planning of Power System Boundaries

Electric energy and Power Systems generally are integral parts of the modern civilization and objects that are continuously developed. For this reason, the scientific optimization of such systems is necessary and constitutes a significant scientific subject. Power System Optimization is a procedure which tries to achieve the best mix of power system supply, cost-effectively with an emphasis on the environmental consequences. That is graphically represented by the triangle of Energy (figure 2.2) [9].

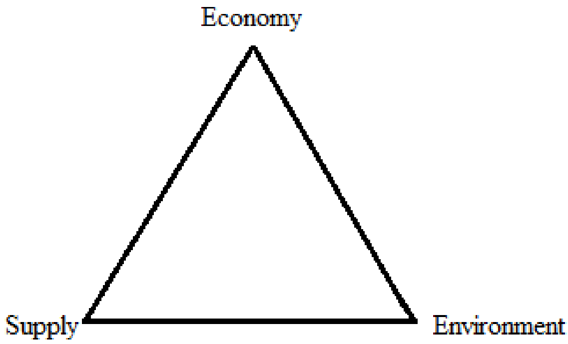


Figure 2.2: Energy supply triangle [9]

Al-Shaalan and Abdullah M (2011), state that power system planning is divided into six different procedures:

The first has to do with the comprehension and analysis of the problem. The plan should create a better economic future and have as a fundamental the expansion of the system with more environmentally friendly solutions (RES).

The second should declare all the goals and the way to achieve them under certain limitations. For example, in the present thesis, the primary goal is the low-cost expansion of the power system. That means the expansion of the system while covering the demand.

Third, is the development of a mathematical model which will study and assess the proper actions under specific definitions and restrictions.

The fourth step is the collection of the proper data. These data should be accurate because they shape the expected results of the model.

The fifth step is to stipulate to the results. That means that the solution should be based on accurate data and under the accordance of objectives and constraints of the problem.

Lastly, the sixth step is that all the results should be accurate and must be analyzed according to all the previous steps or modified if it is necessary [10].

Power system planning is a general study of the power system at specific future conditions with all time data. These plans consist of three different approaches. The short-term approach which deals with the daily utility of power plants in the hourly or daily base. The mid-term approach which studies the temporal or the annual availability of power plants (according to the warm or cold reserves) and the long-term approach which studies the total power system with reference to the future (expansion of the system, units withdrawal), conditions necessary to avoid supply and demand problems.

The present study uses the long-term approach to accomplish an assessment of the Greek Electricity System. The development of power units including RES in an attempt to decrease the gap between demand and supply in a cost-efficient way, is the primary purpose. The complete power master planning also includes the transmission and distribution of the power system, however, for simplification reasons these aspects will not be considered.

The main problems in this situation are the uncertainties of RES and the transmission from fossil fuel production to a RES production while, at the same time facing an increase in energy demand. Also, the imposed policies from the countries and the unions behind them, deem it more challenging to reach a reliable solution for the power system master plan of each country. The above mentioned issues are the main points to be discussed in the present master thesis.

3 Development of the model

In the present thesis a master plan of the electric power system of Greece is developed, attempting to provide the optimal solution with regard to the expansion plan of a power system. Minimization of the total cost of electricity generation, under certain restrictions and boundary conditions, constitutes the primary goal of the optimal approach. Power plants, demand curves, and limiting factors will be used under numerical methods to generate a model. For simplicity reasons and computing time conservation, the constraints and objective function will be linear, leading to a single objective linear optimization approach. The analysis will be based on an existing study, which developed a similar model for the Jordan power system.

3.1 Analysis of model

The development of the model concept, as mentioned above, is an optimization method using linear programming technics. Its objective purpose is the minimization of the power system cost and a better integration of RES into the system, in order to achieve the goal of the model and cover all the technical and environmental characteristics and constraints of the system. The program used for the present study is Microsoft Excel and Solver. Solver is a Microsoft add-in program that can use the Simplex algorithm to optimize linear programming problems. The optimization method used is the time-step method and its function is explained in section 2.1.2. It is also the limitations of Solver, concerning the number of constraints that can be used, which lead to the use of the time-step approach. Because at any time of year the most important factor is the energy security supply, the capacity of the plants constitutes the decision variable.

For the present study, certain assumptions have been made to keep the model as simple as possible. The first has to do with the self-sustainability of the system. That means that the transition power exchange with the interconnected countries has not been taken into consideration. In addition, the study focuses on the type of power plant that will be used in the future, considering at the same time that the full load hour factor is the same throughout the year. Ultimately, the new investment in plants and units that have completed their lifetime is withdrawn from the system. During the present chapter all of these factors will be analyzed more elaborately.

3.2 Objective Function

The objective function consists of the cost of all units in the time frame of the assessment and specifically CAPEX and OPEX, with m being the total number of plants [9].

$$\min \ = \left[\sum_{i=1}^{m} CAPEX_i + OPEX_i \right] \quad (3.1)\ [9]$$

3.2.1 Fixed & Variable costs

Fixed and Variable costs constitute all cost that influences the power system. CAPEX, which is the capital investment cost, is calculated for the new units in the system. This cost consists of the specific investment cost in €/MWh, which is multiplied by the capacity of the plant, the lifetime of the construction and the annuity factor for the total investment cost. The equation expressing this function is the following (3.2) where *Iinv,p* is the investment cost, X_P is the capacity of the plant in MW, Δt is the lifetime in years and AN is the annuity factor which is used for the comparison of capital investment cost of the different plants [9].

$$CAPEX = \tilde{I}_{inv,p} * X_P * \Delta t * AN \quad (3.2)\ [9]$$

Specific investment cost is calculated by dividing the investment cost by the FLH of the plant (equation (3.3)) [9]. Equation 3.4 presents the annuity factor with factor d describing the discount rate, and L standing for the lifetime of the project. There is a divergence in the expected life span of technology power plants; however, it is assumed the expected life span for same type power plants is rather the same [9].

$$\tilde{I}_{inv,p} = \frac{I_{inv,p}}{FLH} \quad (3.3)\ [9]$$

$$AN = \frac{d*(1+d)^L}{(1+d)^L - 1} \quad (3.4)\ [9]$$

On the other hand, operational costs include factors that have been influenced in the entire life span of the project. The O&M costs, fuel and emission costs, compose an equation which describes the total operational costs (equation (3.5)).

$$C_{OPEX_P} = C_{O\&M_P} + C_{F_P} + C_{e_P} \quad (3.5)\ [9]$$

Operational and maintenance costs for a plant can be divided into two subcategories. The first subcategory is the fixed operation and maintenance costs which include the secondary costs of the units and the construction costs. That is presented in the equation

$$c_{O\&M_{fix}} = OPEX_{f_{ix}} * x_P \quad (3.6)\ [7].$$

Variable costs are the costs that each power plant has throughout its life span. These costs include all maintenance activities, as well as the results of the operation of the plants (e.g waste treatment expenses). Equation (3.7) demonstrates these costs. [9].

$$c_{O\&M_{VAR}} = OPEX_{O\&M_{VAR}} * X_P * \Delta t \quad (3.7)$$

For better assess and optimization results, this study will take into consideration the impact of the fuel prices in the variable operational costs. One of the characteristics of fuel prices is their fluctuating character. Specifically, fossil fuels have the oddity to increase their cost over time. One objective is to evaluate the fluctuating fuel prices and their influence on the development of the power system. For the calculation of annual fuel cost of a power plant, the function is the specific fuel price (usually measured in €/kg or €/m2) which takes into consideration the LHV of the fuel and the electrical efficiency of the plant, multiplied by the capacity and the lifetime of the plant (equation (3.10)).

Cost calculations for that particular fuel include some more important features; the fuel fluctuation cost which is described in the equation (3.11) and the growth coefficient λ for a specific year in the future [7].

$$C_{F_P} = \left[C_{F,f} * 3600 \Big/ LHV_f * \eta_{el_P} \right] * X_P * \Delta t (3.8)$$

$$C_{F,f} = c_{F,p} * e^{\lambda * n} (3.9) \qquad [9]$$

$$\lambda = \ln\left(\frac{r_{f_f}}{100} + 1 \right) (3.10)$$

The other basic element of variable costs is the cost that every power unit pays for its emissions. This cost depends on country or international policies, estimated in €/tCO_2 and is paid for according to power unit and fuel type. These emissions are different from the emission factor (tCO_2/GJ or tCO_2/MWh_{th}), which is calculated by the division of cost emissions to the efficiency of electricity of each power plant.

$$EF_{EL} = \frac{EF_F}{\eta_{el_P}} \text{ (3.11) [9]}$$

Now, the calculation of the specific emission cost, came from the multiplication of the emission factor (EFfuel~Tco2/MWh_{th}) by the cost of CO2 (€/tCO_2) .

$$C_{CO_{2i}} = EF_{EL} * C_C \text{ (3.12)}$$

Finally, the total emission costs can be calculated by the multiplication of specific emission cost CCO2 by the capacity of the plant and the lifetime of it equation (3.13).

$$C_{e,P} = C_C * \Delta t * X_P \text{ (3.13) [9]}$$

3.3 Model Constraints

Concerning the minimization operation of the optimization problem, for electricity cost purposes, there are certain constraints which consist of boundaries, equations and inequations. These elements will be analysed more extensively in the following paragraphs.

3.3.1 Power Plant limits

With the term boundaries the upper and lower boundaries of the model are defined, and they are concerned with the electricity output on a yearly basis. There are different boundaries for the stock and for the new power plants. The boundaries for the stock plants are defined depending on their capacity. The lower boundary is zero and the upper boundary is the nominal capacity of the power plant (inequality (3.14)). The variable expressing this figure is the X_p [9].

$$0 \leq X_P \leq P_{NOM_{MAX}} \quad (3.14)$$

The power units that are not in operation (manufacturing state, design phase etc.) take the value 0. That means they do not participate in the simulation. This assumption prevents the negative values in the model and prevents the extraction of values that would be impossible to use [7]. The nominal capacity of the plant is drawn from the sum of the units of that particular plant (equation (3.15) [9].

$$P_{NOM_{MAX}} = \sum_{j=1}^{k} P_J \quad (3.15)$$

Because a quite often problem is data unavailability concerning the new power plants, the sum of the units is the total nominal capacity of the plant. The upper limit in a situation like this is the sum of the nominal capacities of the units and the lowest limit is 0 [9].

The following equation provides the input where, at that the end of the lifetime of a power plant, the upper boundary is considered to be 0. That gives the opportunity to extract one or more units from a power plant, in order to draw more accurate results. For new candidate plants, the upper boundary is 0 until their introduction in the power system. After being integrated in the system, the upper limit is the nominal capacity.

$$0 \leq X_{P,NEW} \leq P_{NOM_{MAX}} \quad (3.16)$$

3.3.2 Security and Stability of the system

Every power system should be able to cover demand with its electricity generation. That applies not only for the existing units but also for the new incoming units of the system. Equation (3.17) clarifies the previous assumption using at the same time the installed capacity and the expected peak demand in the time of the scheduling of the system. It is important to mention that the following equation does not take into consideration electricity imports or exports [9].

$$\sum_{p=1}^{N} Xp * PLF \stackrel{!}{=} [1 + \frac{RR_{PEAK}}{100}] * P_{D,PEAK} \quad (3.17)$$

PLF is the Load Factor of the power plant. It is presented as a percentage number describing the time operation of the plant. RR_{peak} is the reserve of peak demand, which is also formed as a percentage. For that particular equation it is also necessary to mention the following things. Power plants, due to unexpected factors, are not always operational or available to cover the peak demand. Also, as it is widely known, demand changes in the operation of the system with different variations. For that reason, an assumption is made that the peak demand always rises, in order to cover electricity needs. Equations (3.18) explain this situation.

$$\begin{aligned} P_{D,PEAK} &= P_{D,PEAK,0} * e^{\mu_i * n} \\ \mu_i &= \ln(1 + \frac{r_i}{100}) \end{aligned} \quad (3.18)$$

Equation 3.18 clearly explains the cover of the peak demand. Factor ri describes the per-centage rate growth of the load. That rate can change several times during the procedure of the power plan. In the present study the rate is kept stable each year. Additionally, the load factor in a specific moment of the study is defined as the nominal capacity of the power plant. That is of major importance for the integration of RES into the power system due to its fluctuating character. It is very important to use a load factor with a lasting value at the present time in order to fulfill the following study.

3.3.3 Upper and Lower type technology boundaries

Due to the multiple problems that energy sectors face in each country it is obligatory to form an inequation to cover the upper and lower boundaries for every technology type of the installations. Equation 3.19 states that the maximum capacity of an available type is $Xe_{,max}$ and the lower capacity is $Xe_{,min.}$ The adding capacity is expressed by the letter e. Problems potentially affecting the present inequation, can be fuel availabily, political decisions or infrastructure problems. The utility of this inequation has a dual purpose. The first is to prevent wrong calculations in the model, according to the availability of certain technology types and the availability of certain technology. For example, it is not possible to construct a lignite plant in an area that does not have lignite mines within small distance, simply because that would lead in rise of the cost. The second purpose is to preserve power plants, which is very important in order to cover the peak demand in very small time scales [9].

$$X_{e,\min} \leq \sum_{e=1}^{i} X_e \leq X_{e,\max} \quad (3.19)$$

3.3.4 Renewable energy goal

Each country sets certain goals concerning the integration of RES into the system during a specific year. Equation 3.20 gives the minimum value that RES should cover in a specific year [9].

$$\sum X_{\mathrm{Res}} \geq P_{D,PEAK} * f_{RE} \quad (3.20)$$

Factor XRES is the value presenting the available capacity and future RES plants. Factor f_{RE} presents the annual target of RES goal in percentage form. This number was stockpiled linearly every year in order to ensure the integration of RES in the system at the right time [9].

3.3.5 CO2 emissions and energy demand

Equation (3.21) presents the meeting of the energy demand according to the FLH of each power plant. The system should be able to cover the total demand. The FLH was calculated based on previous year data, its only restriction being the covering of the energy demand. After the calculation of FLH, follows the multiplication by the nominal capacity of the plant and the next step is the summing of all values, which gives the total energy demand for that year.

$$E_{D,a} = \sum_{p=1}^{N} P_{N,p} * t_{FLH,p} \quad (3.21)$$

After calculating the demand, there is one last constraint concerning CO_2 emissions. The importance of CO_2 has to do with energy policies that, countries and unions have expressed during the past few years and, are now an essential subject of every power expansion study [9]. For the calculations of CO_2 emissions (in tons of CO_2 equivalent) it is also necessary to use the EF_{el} from equation 3.11. The following equation gives the CO_2 emissions in tons [9].

$$m_{CO_2} = \sum_{p=1}^{N} EF_{el,p} * P_{N,P} * t_{FLH,p} \quad (3.22)$$

4 Case Study Greece

The following case study is concerned with the Greek Electricity System. In this study, all the parameters of the system are extensively analyzed, with the scope of using the current situation data as the starting point for the optimization model and for the future scenarios that will be assessed. In addition, the newly created portfolio will be assessed according to the future expansion of power plants, that are currently being studied for the development of new power units in the future, assisting in that way to achieve a more realistic solution.

4.1 Historical review of Electricity in Greece

According to the historical archives of RAE, the first time electricity was utilized in a Greek region was back in 1889. The "General Contractor Company", was the primary power plant and it was the one to light up the Palace of Athens for the first time. A couple of months later, electric power was spread out to what is currently called the center of the city, and in Thessaloniki, despite the fact that it was still under Ottoman co-trol. A few years later, the American organization Thomson-Houston, with the cooperation of the National Bank of Greece, established the "Hellenic Electric Company", which distributed electricity in a substantial number of Greek urban areas. By 1929, 250 urban communities with a population of more than 5,000 were lit up. Regarding remote regions, private companies considered at that time that it was unprofitable to contribute in providing them with electricity thus, municipal and local authorities started develop-ping little power units. By the end of 1950, there were more than 400 organizations utilizing coal and oil for electricity production in Greece. In August 1950, PPC (Public Power Corporation) was established, which undertook all electricity generation, trans-mission and distribution activities. PPC began the utilization of local energy sources with base fuels, lignite and the hydroelectric power while, consolidating at the same time the integration of electricity networks into an interconnected national system. [11]

The liberalization of the electricity market and the second directive of EU in 2004, gave the opportunity to other producers to take a share of electricity production. That in-creased the energy safety and alleviated the market economically, under institutional rules, which deemed necessary the avoidance of the problems of 1980-2000. That, allowed for more than 24 companies to become licensed to supply electricity, with the majority of them being in the energy trading sector [12].

However, one of the problems Greece is facing at the moment is the lack of future power planning. Despite all the plans that have been filed over time (i.e. energy plan of 2012 National Report to the European Commission), there is not a single formal or institutioalized energy plan. This study is a proposal that could evolve into an overall energy plan.

4.1.1 Electricity System

Oikonomou, Malamou & Karvouniari define Electricity System as the amount of procedures and installations which are used for electricity production and serve electricity consumer needs. The System is based on three pillars of reliable electricity supply in any place, regardless of any difficulty, with minimum cost and minimum environmental impact. Electricity systems are distinguished in Production, Transmission and Distribution Systems. Production Systems include power plant stations, where electricity is produced and after voltage transformation, specific stations produce High Voltage. Transmission Systems includes the HV lines, grid link substations, transformation substations in different voltage levels and relegation substations for Medium Voltage and international interconnections. Finally, distribution systems contain MV and Low Voltage grids including substations relegation for low voltage consumers [13,51].

4.2 Greek Electricity System

The continuous economic growth in Greece has had a major impact on electricity consumption as is the case in all the developed and developing countries [12]. The Greek Electricity System is based on lignite, natural gas and hydroelectric production of electricity, including a high-level integration of RES in the interconnected system and integration of heavy fuel oil and diesel units in the non-interconnected system[13]. The main electricity production takes place in the region of Kozani in Western Macedonia, with 50% of electricity coming from lignite extracted from that particular area. In addition, lignite units can also be found in Elassona, Drama and Megalopoli, Peloponnese with a percentage of 16% in the total mix of the system. In Greece, according to the RAE data of 2012, 66,5% of the total installed capacity comes from thermal units, 19.6% from hydroelectric power stations and 13.9% from RES [15,16].

Figure 4.1 illustrates the reduction of the annual demand per year. The decreased rates that can be observed are a result of many factors. Financial crisis, reduction of household income and reduction of HV consumers are some of them [16]. It can also be noticed that the annual demand has a decreasing rate. Another factor explaning these results is the increasingly scattered production of RES which creates a fluctuating situation in the operation of the system. This has changed since 2015 due to the smoothing of the economic situation and the reduction in RES investments [17].

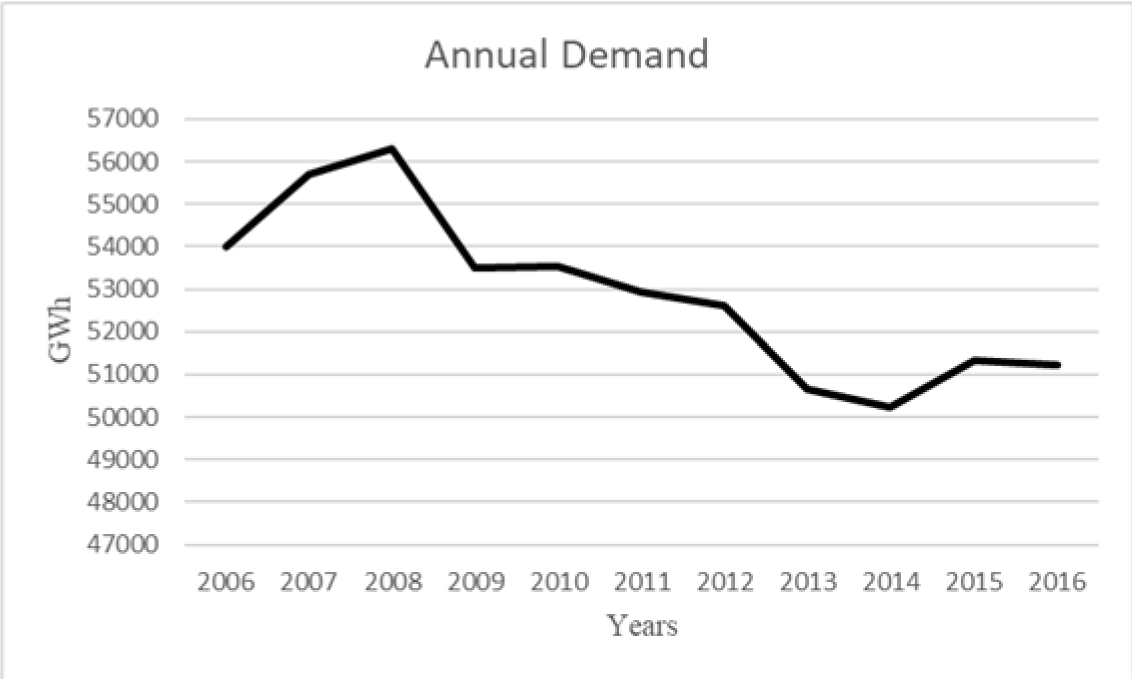


Figure 4.1: Greek total net electricity Demand in GWh 2006-2016 [2]

In the last decade, the decrease rate is -0.93% every year with only two exceptions; 2006-2008 with a percentage rate of 2.13% and 2015 with a percentage rate of 1.91% according to the latest precision power study of IPTO.

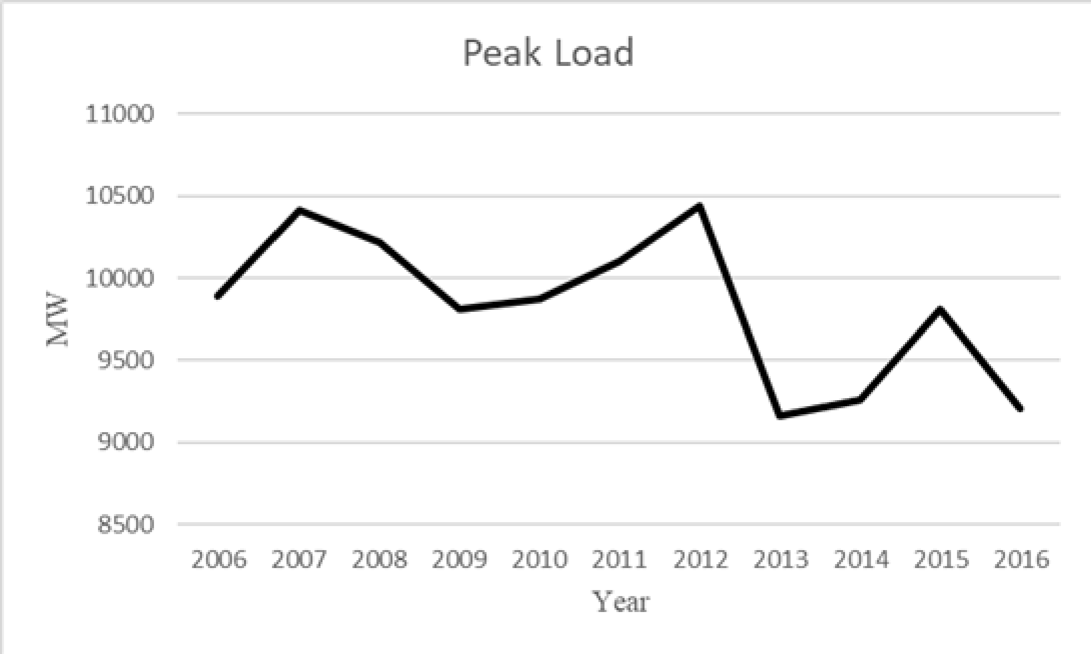


Figure 4.2: Greek electricity Peak Load in MW 2006-2016 [16]

Apparently, both peak load and demand present a certain peculiarity in their nature. The total decrease rate for peak load is -1.87% with the biggest decrease occurring in the period 2012-2013 with a rate of -12.23%. As the TSO of Greece states at the Precision Study of 2017, the peak demand usually occurs in summer due to air-conditioner use, and especially during high-season periods, such as June and July. The only exception to that was year 2004, when the peak load period was in August due to the Olympic Games. Since 2013, the peak load period has shifted onto winter because consumers started shifted from using fossil fuels for heating purposes to using electric power-operated resources instead; something that is expected to gain more popularity and usage increase in the future. [2,52].

For information study reasons, the following curve presents the load curve for the year 2015, the reference year of our model. The present annual load duration curve is created from the daily data of load according to IPTO daily clearing procedures. From the chronological load curve figure for the year 2015, it is deduced that the peak is at 10425 MW and the lower value is 3884 MW.

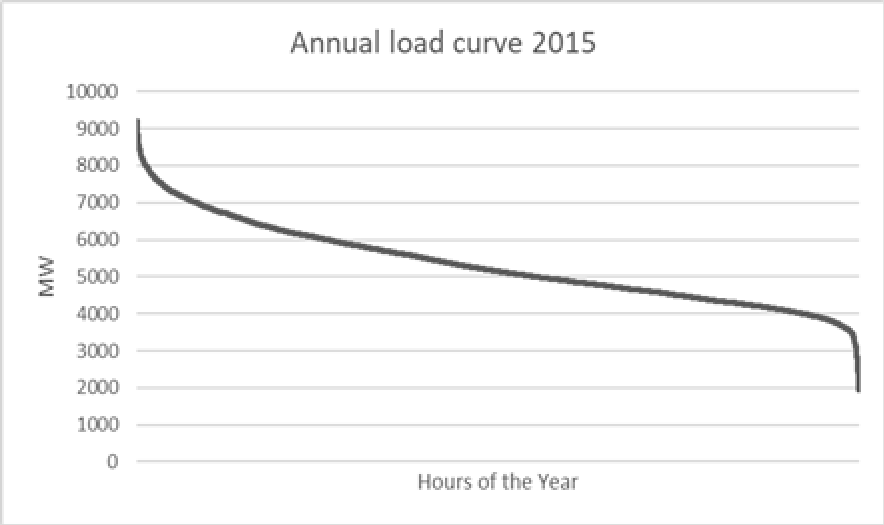


Figure 4.3: Chronological Load Curve (2015)

4.2.1 Current situation of Greek Power System

The Greek power system is currently in a state where transition is bound to take place. The annual demand and the annual peak load have decreased in the past few years, but the forecasts indicate a different path in the development of the system. The liberalization of electricity market, the increased shares of private producers and the latest support scheme that the Greek government and the EU are trying to impose on the most significant producer in Greece, the PPC, are almost certain to cause remarkable changes in the energy sector. [19,52]

During the past year, the total installed capacity was 11323 MW, with the total energy production in the electricity sector reaching 46641 GWh. Table 4.1 presents the 2016 power plant portfolio for the total electricity system (interconnected and non-connected systems – distributed units) for all the units above 10 MW. In addition, that table includes all the power units, regardless of their technology and their fuel, as well as the hydroelectric units which have a big share in the total mix of the country.

Producer	Power Plant	Unit	Fuel	Ins. Cap.(MW)	Tech. Availability (MW)	Year of induction	n_{el} in %	FLH in h
PPC	Agios Dimitrios	1	LIG	300	274	1984	34,77	2938,562044
PPC	Agios Dimitrios	2	LIG	300	274	1984	34,77	3955,321168
PPC	Agios Dimitrios	3	LIG	310	283	1985	35,22	5276,201413
PPC	Agios Dimitrios	4	LIG	310	283	1986	35,22	3605,402827
PPC	Agios Dimitrios	5	LIG	375	342	1997	35,22	4000
PPC	Amyntaion	1	LIG	300	300	1987	35,22	3040,853333
PPC	Amyntaion	2	LIG	300	300	1987	35,22	2750,173333
PPC	Kardia	1	LIG	300	271	1975	35,22	3706,332108
PPC	Kardia	2	LIG	300	271	1975	35,22	2982,612546
PPC	Kardia	3	LIG	306	280	1980	33,97	3109,342857
PPC	Kardia	4	LIG	306	280	1981	33,97	3601,878571
PPC	Megalopoli	3	LIG	300	255	1975	33,97	4192,94902
PPC	Megalopoli	4	LIG	300	256	1976	35,65	4643,300781
PPC	Meliti	1	LIG	330	289	2003	38,6	4294,110727
Total ins. Cap. from Lig.				4337	3904			0
PPC	Komotini	Komotini	CCGT	484,6	476,3	2002	56	3407,988663
Elpedison	ENTHES	ENTHES	CCGT	408,4	400,3	2005	56	2823,132651
Elpedison	THISVI	THISVI	CCGT	421,6	410	2011	56	3313,060976
HERON	HERON II	HERON II	CCGT	432	422,11	2004	58	3183,459288
Korinthos Power	Ag.Theodoroi	Ag.Theodoroi	CCGT	444,5	432,7	2011	56	3548,883753
Total ins. Cap. from CCGT				2191,1	2141,41			0
PPC	Lavrio	4	OCGT	560	550,2	1999	38	2273,356961
PPC	Lavrio	5	OCGT	385,2	377,6	2004	38	198,5778602
PPC	Aliveri	5	OCGT	426,9	417	2014	40	3527,685851
Protergia	Ag.Nikolaos	Ag.Nikolaos	CCGT	436,6	433,5	2011	40	3047,78774
HERON	HERON	HERON	OCGT	148,5	147,8	2004	38	38,12584574
Total ins. Cap. from OCGT				1957,2	1926,1			0
ALUMINION	ALUMINION	ALUMINION	CHPG	334	334	2008	45	3429,916168
Total ins. Cap. from CHPG				334	334			0
PPC	Agra	1	HYDRO	25	25	1956		592,08
PPC	Agra	2	HYDRO	25	25	1956		592,8
PPC	Asomaton	1	HYDRO	54	54	1985		1456,675926
PPC	Asomaton	2	HYDRO	54	54	1985		1456,675926
PPC	Edessaios	1	HYDRO	19	19	1969		1151,842105
PPC	Thisavros	1	HYDRO	128	128	1987		1018,054688
PPC	Thisavros	2	HYDRO	128	128	1987		1018,054688
PPC	Thisavros	3	HYDRO	128	128	1987		1018,054688
PPC	Kastraki	1	HYDRO	80	80	1970		2208,1
PPC	Kastraki	2	HYDRO	80	80	1970		2208,1
PPC	Kastraki	3	HYDRO	80	80	1970		2208,1
PPC	Kastraki	4	HYDRO	80	80	1970		2208,1
PPC	Kremasta	1	HYDRO	109,3	109,3	1965		2218,398902
PPC	Kremasta	2	HYDRO	109,3	109,3	1965		2218,398902
PPC	Kremasta	3	HYDRO	109,3	109,3	1965		2218,398902
PPC	Kremasta	4	HYDRO	109,3	109,3	1965		2218,398902
PPC	Ladonas	1	HYDRO	35	35	1956		2927,771429
PPC	Ladonas	2	HYDRO	35	35	1956		2927,771429
PPC	Pigon Aoos	1	HYDRO	105	105	1990		1101,095238
PPC	Pigon Aoos	2	HYDRO	105	105	1990		1101,095238
PPC	Plastiras	1	HYDRO	43,3	43,3	1962		1415,473441
PPC	Plastiras	2	HYDRO	43,3	43,3	1962		1415,473441
PPC	Plastiras	3	HYDRO	43,3	43,3	1962		1415,473441
PPC	Platanovrisi	1	HYDRO	58	58	1999		1960,224138
PPC	Platanovrisi	2	HYDRO	58	58	1999		1960,224138
PPC	Polifitos	1	HYDRO	125	125	1974		1114,104
PPC	Polifitos	2	HYDRO	125	125	1974		1114,104
PPC	Polifitos	3	HYDRO	125	125	1974		1114,104
PPC	Pournari I	1	HYDRO	100	100	1981		1252,82
PPC	Pournari I	2	HYDRO	100	100	1981		1252,82
PPC	Pournari I	3	HYDRO	100	100	1981		1252,82
PPC	Pournari II	1	HYDRO	16	16	2000		1270,0625
PPC	Pournari II	2	HYDRO	16	16	2000		1270,0625
PPC	Pournari II	3	HYDRO	16	16	2000		1270,0625
PPC	Stratos	1	HYDRO	75	75	1988		2086,946667
PPC	Stratos	2	HYDRO	75	75	1988		2086,946667
PPC	Sfikia	1	HYDRO	105	105	1985		717,352381
PPC	Sfikia	2	HYDRO	105	105	1985		717,352381
PPC	Sfikia	3	HYDRO	105	105	1985		717,352381
Total ins. Cap. from HYDRO				3032,1	3032,1			0
PPC	Crete	22*	ST/ICE - HFO/DIESEL **	819	724,74	1968-2008	37-38,5	3140,869829
PPC	Rhodes	10*	ST/ICE - HFO/DIESEL **	206	186,8	1976-1997	37-38,5	3683,865096
PPC	Lesvos	12*	ST/ICE - HFO/DIESEL **	82,2	63,3	1982-2002	37-38,5	3929,404471
PPC	Kos-Kalimnos	15*	ST/ICE - HFO/DIESEL **	120,05	95,3	1976-2005	37-38,5	3342,004197
PPC	Limnos	6*	ST/ICE - HFO/DIESEL **	22,128	20,45	1980-1985	37-38,5	2544,05868
PPC	Milos	5*	ST/ICE - HFO/DIESEL **	20,06	12	1968-2002	37-38,5	3331,333333
PPC	Paros	10*	ST/ICE - HFO/DIESEL **	74,5	68,02	1984-2005	37-38,5	2616,598059
PPC	Chios	8*	ST/ICE - HFO/DIESEL **	63,3	56,45	1976-2008	37-38,5	3194,278122
PPC	Siros	9*	ST/ICE - HFO/DIESEL **	33,297	29,15	1976-2004	37-38,5	2965,317324
PPC	Samos	5*	ST/ICE - HFO/DIESEL **	32,72	28,2	1960-1999	37-38,5	3016,560284
PPC	Karpathos	4*	ST/ICE - HFO/DIESEL **	10,326	95,268	1966-2005	37-38,5	349,0364026
PPC	Mikonos	11*	ST/ICE - HFO/DIESEL **	37,66	29,95	1970-2002	37-38,5	4375,792988
PPC	ONI	***	ST/ICE - HFO/DIESEL **	147,79	***	1960-2008	37-38,5	0
Total ins. Cap. from ST/ICE - HFO/DIESEL				1669,031	1409,628			0
Total Dis. Sys. Cap.				13520,431	12747,238			
*: Total amount of units in nonconnected system								
**: All units are categorized in one category due to their type and their fuel								
***: These units are categorized as one due to their low caparity (<10MW)								

Table 4.1: Greek power plant portfolio 2015 (included connected and non-connected system dispatchable power plants without RES) [2,16,20,21,23,53]

At the end of 2016, electricity production in Greece was based on fossil fuels and especially on lignite. More than 50% of the production was attributed to lignite however, another significant amount had arisen from natural gas and hydroelectric power plants.[17] The following table (4.2) illustrates the power generation by type for 2016 in Greece according to TSO and DSO.

Type	Power Generation (GWh)
LIGNITE	15.007
HFO/DIESEL	4.635,77
NATURAL GAS	12.240,3
HYDRO UNITS	5.239.7
WIND ENERGY	5146.01
BIOGAS	253
SOLAR ENERGY	3893.06
CHPG	1145.5
TOTAL	**47560.34**

Table 4.2: Electric energy production by type of generation in Greece 2016 without the dispersed production [16,21]

During the last decades, Greece has been using lignite as a base fuel for its power generation. Lignite, up to this date, remains the country's basic fuel. However, after the liberalization of market, natural gas came to the foreground, taking market share from lignite and hydroelectric power units of PPC. The two following figures 4.4,4.5 demonstrate the power generation from lignite and natural gas respectively, according to the monthly precision studies of ADMIE for 2016 [23].

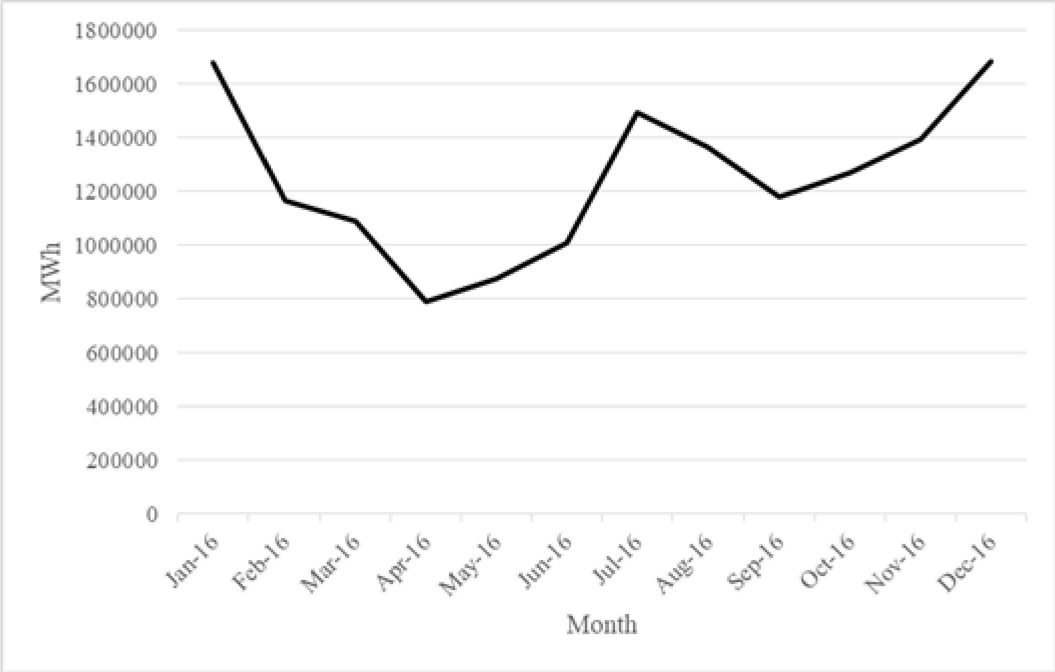


Figure 4.4: Greek lignite power generation in MWh at 2016 [20]

The increased values during winter and autumn are a result of the use of lignite units for thermal purposes in the district heating network of Western Macedonia, as well as a result of covering the peak loads, which in the last years arise during the winter months in Greece, as it was mentioned before. In summer, the use of these units is limited to a minimum, due to wind and solar power permeating the system.

The installed capacity of 52%, as TSO presented in the annual report of 2016 [16], also includes the natural gas units which have influenced the electricity production in many ways. The electricity produced from natural gas for 2016 is given in the figure 4.5.

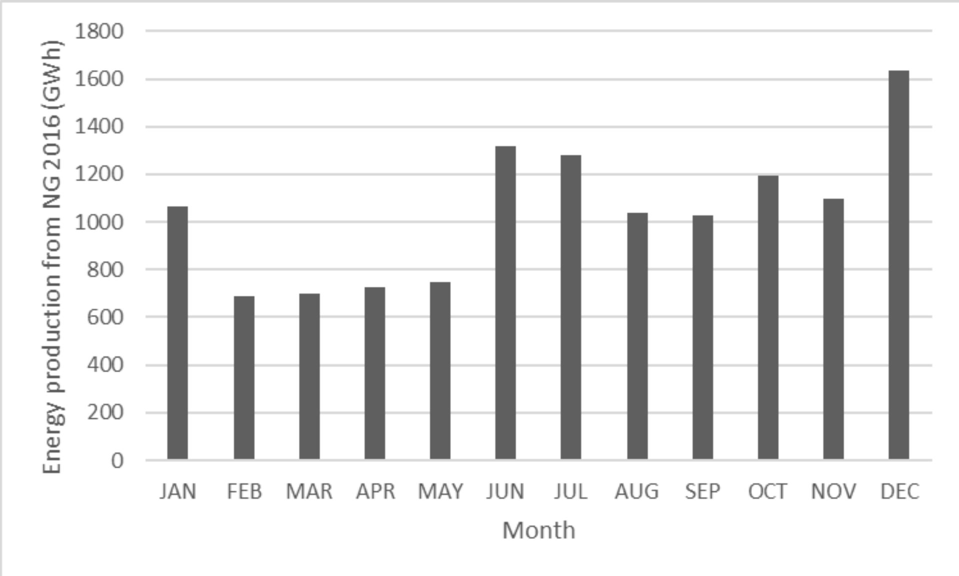


Figure 4.5: Greek natural gas power generation in MWh for 2016 [16,20,]

It can be observed that, in the process of generating electricity with natural gas, the most significant values occur during summer and winter, in order to cover the demand of the system. However, there is also an increase in cost because Greece is currently not able to produce natural gas.

The cost of natural gas electricity production amounts to 21,76 €/MWh (according to the latest data of 2014) and for lignite to 59,93 €/MWh for 2017[23,24]. As a result of these values being very high, the cost of primary energy is largely elevated. The lignite electricity production cost is almost the highest in the EU, just below Germany and Poland, however the mining cost is the lowest, because the low heating value of lignite increases the number of emissions and decreases the amount of useful energy production [25]. Supplementary to what was mentioned above, it should be noted that imports of natural gas, diesel or heavy fuel oil, increase the total cost of primary energy production in Greece. In addition, it is necessary to mention the cost of excise taxes and other charges (special lignite fee, local community taxes etc.) which are also levied on fuels and have an impact on the cost. [26, 56].

4.2.2 Expansion Plans for Electricity System of Greece

Greece, following the example of other European countries, ought to make some adjustments in its future energy policy. The aim is to provide Greece with the opportunity to secure its energy safety and to improve competition in Greek economy. To be more precise, all the EU countries should implement the following by 2020:

- 20% reduction of GHG in accordance with 1990 levels (according to 2009/29/EU norma)
- 20% penetration of RES in the final energy consumption (according to 2009/29/EU norma)
- 20% primary energy saving.

For Greece, the target of reduction of GHG emissions was 4% in relation to 2005 levels and RES was integrated by 18% in the final consumption [15]. To this day, it is safe to assume that the primary goals have been achieved and the Greek government is seeking to enforce higher targets.

In an attempt to enforce EU legislations, Greece established in 2012 the national energy roadmap 2050. The aim of this roadmap is the reduction of imports, the maximization of RES penetration in the system and the reduction of CO_2 emissions by 2050 [56]. With two scenarios in hand (one base case and one for the minimization of cost with environmental aspect) Greece paved the way for energy systems in 10 bullet points [15]:

- 60-70% Reduction of GHG
- 85-100% production of electricity from RES
- 60-70% RES penetration to the net final consumption until 2050
- Stability in energy consumption due to this reduction measures
- Increase in electricity consumption due to the increase of electricity use for transportation and heating
- Reduction of oil share in energy mix
- Increase in the use of electricity in public transportation by 45%
- Increase of energy efficiency in existing buildings
- Development of decentralized units of smart grids

Greece has recently had an increase in its share of imports. The reason why is the high-cost electricity production from lignite use and the demand that the load should be covered at any time in the spread transmission system. The following figure demonstrates the energy mix of 2016, along with the percentage rate of imports in the system.

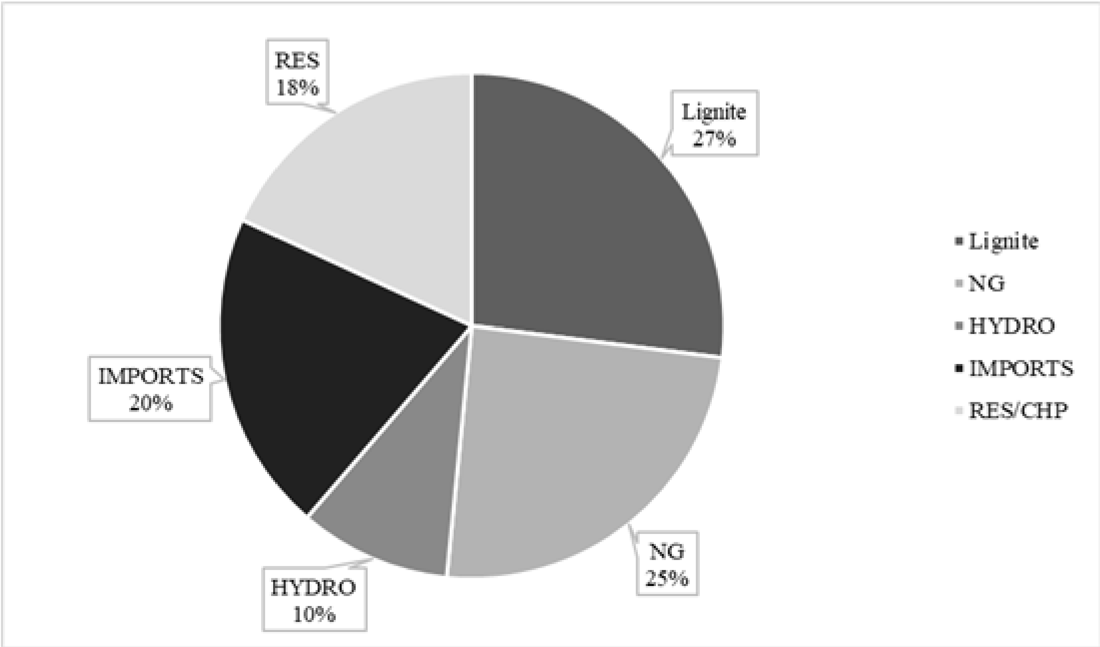


Figure 4.6: Energy mix 2016. Percentage of imports in the system [25]

The number of imports for Greece is high. According to the forecasts of Greek authorities, in the following years the number of overall demand, as well as the peak load, will start increasing. That increase will create problems for the energy production of the system while, the operators and the producers will be forced to handle a situation rather unique for the Greek power system. It is also very important to consider any unexpected problems that might occur in the system, which could have severe consequences in energy production (such as the collapse on the mine of Amynteo last August), as well as the political decisions concerning the power units of PPC.

4.2.3 Lignite Production in Greece

According to Heinrich Boll Stiftung Institute, lignite is the only fossil fuel that can be found in Greece to this day. The low cost of lignite and the local deposits throughout the mainland of Greece made lignite the country's base fuel. Greece ranks 3rd in lignite use in Europe (behind Germany and Poland) and 7th in the world. The future of lignite is uncertain because of the pressure certain factors (public health, penetration of RES, international treaties etc) have placed on EU & Greek legislation to start imposing the decommission of "dirty" lignite units and investing in more friendly sources of energy.

Lignite dependence reaches 62.1% in Greece, a quite high percentage compared to the European average percent. Presently, lignite remains amount to approximately 3.2 billion tons, with an actual forecast for lignite consumption for the next 45 years. In addition, there is data proving the amount of lignite mined to be around 29%. During the past ten years, the share of lignite has decreased from 63% to 45% (in 2014) with the installed capacity in the system being 4337MW.[25]

In the new liberalized energy market, future expansion targets of lignite constitute an unstable factor due to the fact that new units are no longer planned centrally with a future- centered perspective, but mostly concentrate on independent producers and the viability of their investments. The exact timetable for the implementation of already de-cided investments involves considerable uncertainty, due to unforeseen difficulties that may arise either during the licensing process or during the construction stage. In the pre-sent decade there is only one lignite thermal power plant under construction: the new lignite power plant of Ptolemaida (660MW). [16]

4.2.4 Natural Gas

Since Greece has no domestic sources of oil and gas, depending on imports for these two fuels is inevitable. The main imports of gas come from Russia (by 74%) and from Algeria in LNG form [57]. Natural gas has been infiltrating the electricity system in an increasing manner. This is attributed to the liberalization of electricity and natural gas market. The Combined Cycled units provide high efficiency and better environmental results, and engage in the electric power system occupying a percentage rate of nearly 25%. [26,23]

The first company that installed NG units was PPC in 1997, installing the unit of Agios Georgios. The next were the combined plants of Komotini, Megalopoli and Aliveri. In 2004, the first private combined cycle unit of HERON was built and allowed for the Transmission System of Natural gas. The capacity of that unit was 148 MW of electricity. Then, in 2005 ELPEDISON installed its first combined cycle plant in Thessaloniki, with a capacity of 390MW. More units (such as THISVI, ALUMINIUM, HERON II and KORINTHOS POWER) came into being in the following years, thus increasing the Greek power plant portfolio by 2072 MW of electricity.[27]

Due to the uncertainty of the Greek electricity market, a lot of the investments from private producers were blocked. On the other hand, PPC has announced the emerging of natural gas power plant units.. These units will be Megalopoli V and VI, and their installed capacity is expected to be 411 and 800 MW respectively, and they shall be incorporated in the system at the end of 2017 and in the middle of 2019 [16].

4.2.5 Diesel & Heavy Fuel Oil (HFO)

As already mentioned before, there are no other fossil fuels produced in Greece apart from lignite. The use of Diesel & Heavy fuel oils was eliminated from the connected system. The only use of these fossil fuels is observed at the non connected system, in the islands of Greece. These units are property of PPC.

Electricity demand in these regions is covered by RES, diesel or, HFO units which in their majority are small capacity units; with the exception of the three steam turbine units in Crete (Atherinolakkos, Hania, Linoperamata) and the units in Rhodes. [16]

The fuels needed for their operation are imported from Motor Oil and Shell companies. Motor oil provides units of Crete with HFO and all the other units with diesel. On the other hand, Shell Trading Rotterdam BV will provide the rest of the units with HFO. The amount of HFO that PPC power plants need is approximately 1 million tons. The plan to eventually eliminate these units has begun with PPC and DSO planning to cover the demand with smart grid and RES [28]. In the following figure HFO and diesel units are displayed.

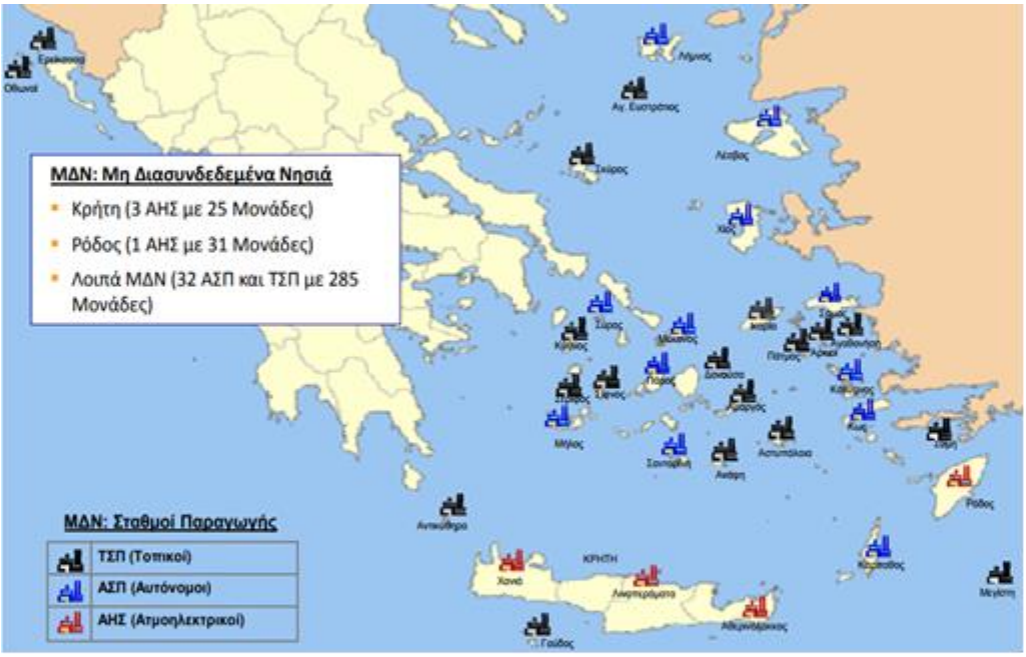


Figure 4.7: Non-Interconnected Power plants.ST power plants are displayed in red color, individual units are displayed in blue color and local units are displayed in black color [27].

4.2.6 Hydro Power

One of the most critical categories of power plants in Greece are hydroelectric power plants. With a percentage rate of 18.1% and installed capacity of 3032.4 MW, hydropower has a significant impact on electricity production.

An important feature that makes the production of electricity from hydroelectric power plants so valuable, is the flexible and fast integration in the system, in order to cover peak demands (in peak load periods) and increase the quality of subsidiary services. In addition, the emission-free “green” energy is beneficial in gaining important environmental and economic profits, which can be reflected in the national economy (emission trading) and peoples’ daily life. Lastly, the exploitation of certain hydroelectric power plants (Sfikia, Thisavros) as reverse power stations can also be profitable, leading in low cost energy during the increased power demand hours of the system.

A future forecast for these units can not be given due to the nature of their construction. The only forecast available has to do with future commissions in the system and especially in the unit of Ilarionas, with capacity 153MW at the end of 2017.[29]

4.2.7 Solar Power

Solar energy plays a major role in the independency of energy in Greece and constitutes a clear environmental solution for power generation. Its advantageous position in South-East Europe gives Greece a great solar potential, compared to other EU countries. The annual solar irradiance at a horizontal plane is calculated around 1450-1800 kWh/m2. Figure 4.8 illustrates the global solar irradiation, with the highest values appearing in the Aegean Islands, especially Rhodes, and in South Crete.

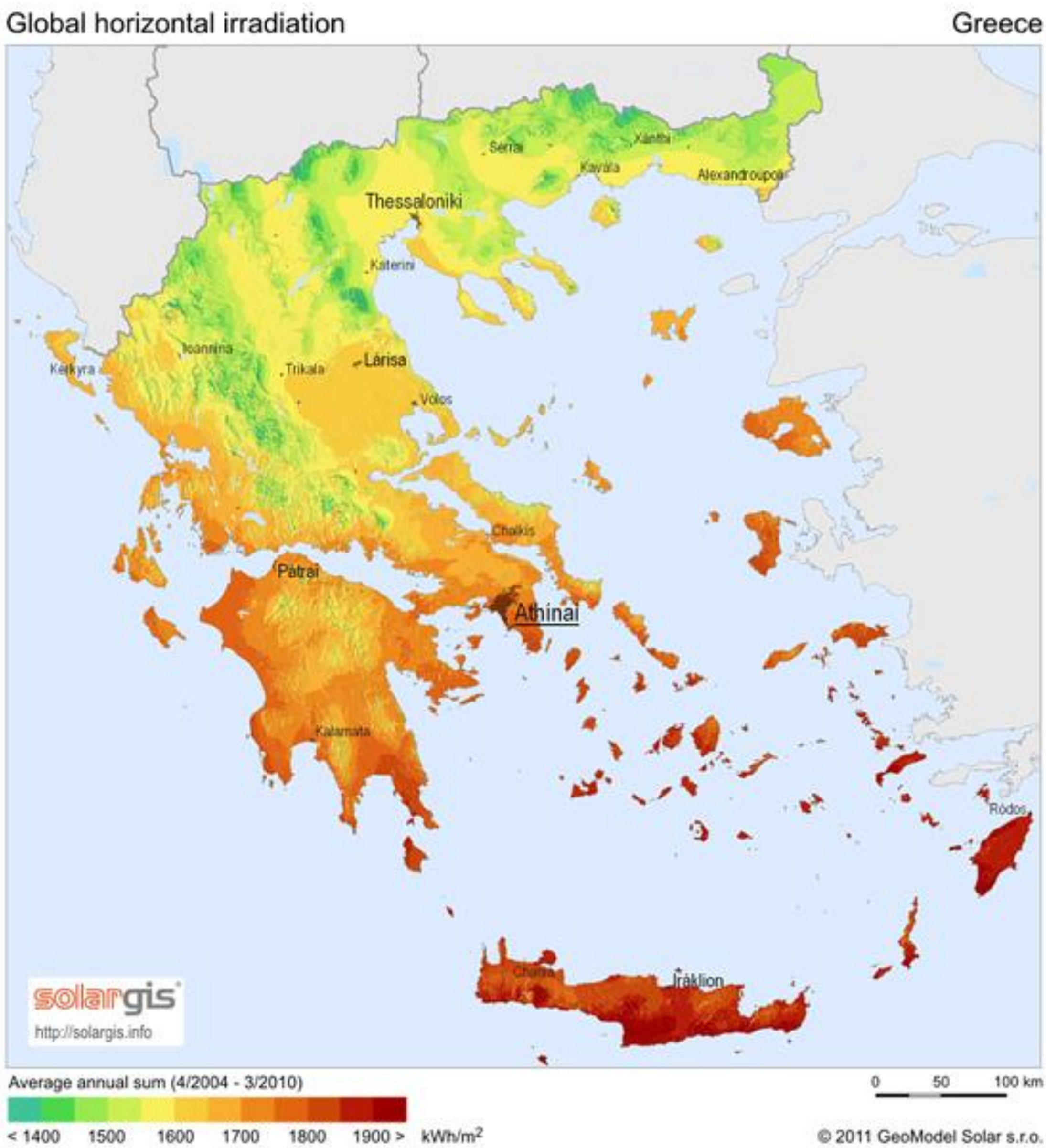
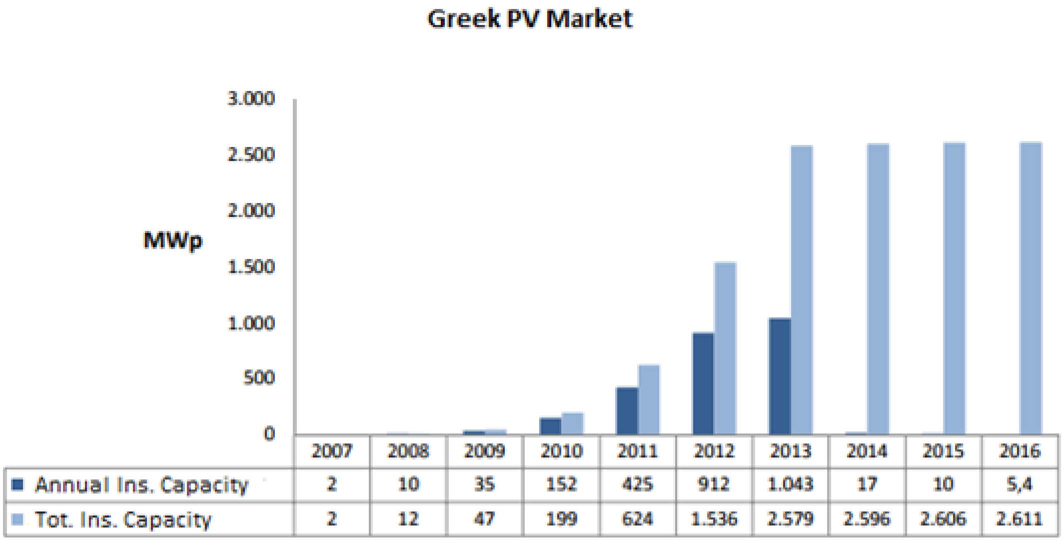


Figure 4.8: Average annual global horizontal irradiance in Greece [30]

The high solar potential and the economic policies for green energy established by the Greek government and the EU, paved the way for the flourishing of new installations in 2007. The installed capacity of PV installations in the interconnected and in the non-connected system increased from 2MW in 2007 to 2580 MW in the end of 2016 [16,25,31], consistently rising in the following years.



	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Annual Ins. Capacity	2	10	35	152	425	912	1.043	17	10	5,4
Tot. Ins. Capacity	2	12	47	199	624	1.536	2.579	2.596	2.606	2.611

Figure 4.9: Greek PV market evolution in terms of annual & total installed capacity [32,33]

According to LAGIE, the divergence from 2580MW to 2611 MW is accounted for by the PV stations installed at the roof-mounted PV systems, for residential or commercial use [33].

These PV stations spread throughout Greece, with the largest installations being located in Crete and the central region of Greece, due to the presence of large areas available. Figure 4.10 arises from RAE software and illustrates all PV stations in Greece.

Figure 4.10: PV power station in Greece [34]

The financial problems that LAGIE (Operator of Electricity market) faces and the reduction in the FiT prices, create a huge problem for the market. The new support scheme of FiP tries to overcome these problems. In addition, the difficulties in license procedures since 2012 and the taxes on PV installations (25%), make the future of PVs look uncertain. [37]

In spite of what was mentioned above, Greece has already achieved the main goals of EU regulations for 2020 (the base scenario 0.7GW and the compliance scenario 2.2GW), seven years before the designated date. The country is now very close to achieving the accelerated scenario of 2.9GW total installed capacity. In addition, project Helios, despite the stagnation and any diffuculties, constitutes a positive stimulus for the future of solar energy, despite the problems that were mentioned above.[34]

4.2.8 Wind Power

One of the biggest potentials of RES is wind power. The geographical position of Greece and the meteorological situation make wind power a highly competitive technology in energy production. Despite the current situation in Greece, a small increase of wind power capacity can be observed, in accordance with the average wind potential of the country.

The first wind power plant was created by PPC in 1982 in the island of Kithnos, in order to reach the 2375MW total installed capacity of all power plants by 2016. The biggest portion of this wind power installation is located in central Greece with 737MW total capacity, while the lowest is located in Thessalia (total capacity of 18.6MW). TERNA has the biggest portfolio of all wind power plants with 460MW total installed capacity [35].

The most substantial wind potential lies in the Greek islands and especially the Aegean islands, which have an average potential of 9m/s; the same wind average speed is observed up north and in some other regions of Central Greece. [36]. Figure 4.11 displays wind potential in Greece.

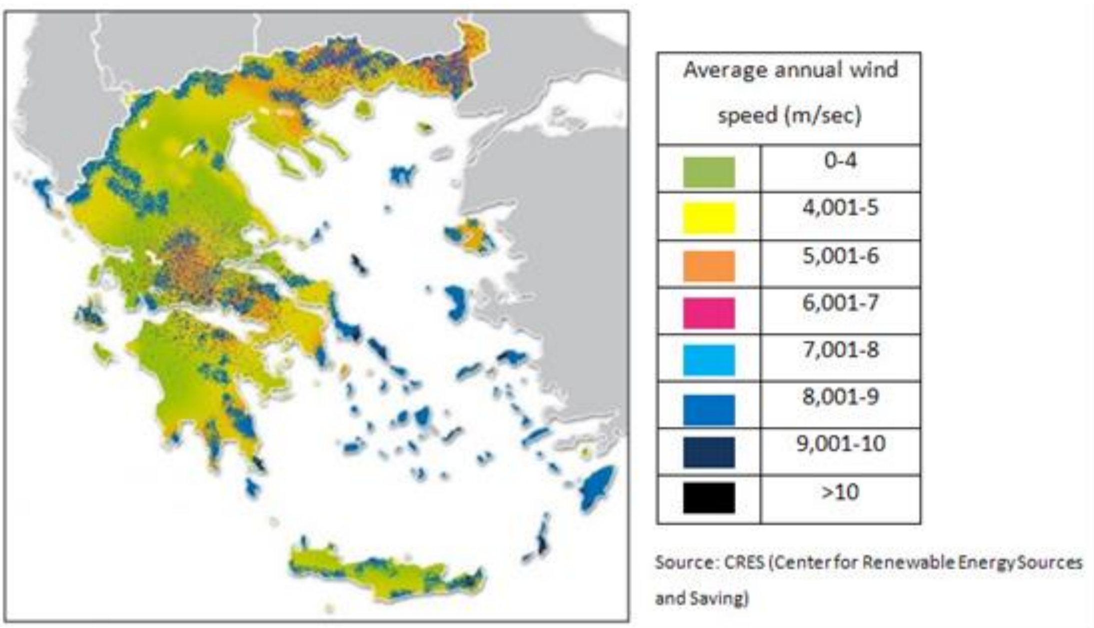


Figure 4.11: Average wind potential in Greece [37]

Since wind power plants constitute a competitive technology, an increase in their penetration share in the system is likely to happen. According to the 2016 annual report of Greek Wind Energy Assosiation, the total capacity was 238.6MW; the second best annual performance since 2011. The idea is that the wind capacity will overcome 1GW in the years 2017-2020. Lastly, their important role will be more clearly observed among 2016-2023, due to the decommission of Aminteo and Kardia units.[39] Consequently, the new installation of power plants is necessary in order to cover the demand, and this will be more apparent in the years to come, due to the nature of disperced production of the wind power plants. In order to achieve better results, it is also necessary for the government to make some important decisions and to introduce all these units in the system under a preferential treatment.[39]

4.2.9 Biomass & Biogas

Despite its considerable potential, Greece holds only a small amount of biomass and biogas resources for power generation. According to the Greek Development Biomass Association, in Greece only 58MW of thermal power is produced from biogas, whereas the amount produced from electricity is almost zero. [38,40] Taking this into account, Greece ranked last in the EU in biomass energy production, along with Malta and Cyprus.

4.2.10 Geothermal Energy

Geothermal energy is practically an unlimited source of energy which, supported by the current technological improvement, can be used for power generation. Greece has a geo-thermal potential of 25^{o}C – 360^{o}C, which can be used for electricity production. This geothermal energy can mainly be observed in the volcanic arc of the South Aegean (Milos-Santorini). To this day, there are no geothermal power plants in Greece, just a few installations for thermal purposes (cultivations in greenhouses) [41].

4.3 Forecasts

In the present chapter, the forecasts for the expansion of the Greek energy system, as well as the development of costs, are going to be analyzed. The uncertainty and the lack of data in many parts of the system create assumptions based on a more accurate forecast.

4.3.1 Future load and consumption

The latest report on power adequacy from TSO established that, in the future the system will expand thus, it should be able to cover the increased demand. The study of TSO concerns the time period from 2017 to 2027 and takes into consideration all the present parameters of the market, as it tries to investigate the future characteristics, in scenarios that are based on the fluctuating character of the system. There are three TSO scenarios. In our situation the base scenario will be considered, since its values are more realistic. The scenarios to be assessed in the following chapter are based on Roadmap 2050, for the deduction of more realistic results. In accordance with, the TSO scenario, the development of the demand and power generation (in MWh) is presented in the following table (4.3). It is worth noting that this scenario takes into consideration the transmission connection of Crete to the connected system from 2025 onwards. The implication is that the total load of Crete is undertaken by the connected system, without the use of the local units of Crete [16].

Year	**Demand**		**Power Generation**	
	MW	**Percentage of Growth (%)**	**MWh**	**Percentage of Growth (%)**
2017	9868	7,17	52600	13,17
2018	10079	2,14	53720	2,13
2019	10260	1,80	54700	1,82
2020	10610	3,41	57290	4,73
2021	10720	1,04	57865	1,00
2022	10790	0,65	58230	0,63
2023	10860	0,65	58590	0,62
2024	10920	0,55	58960	0,63
2025	11510	5,40	61010	3,48
2026	11590	0,70	61440	0,70
2027	11670	0,69	61840	0,65

Table 4.3: Electricity total annual demand and power generation forecast and growth rates in Greece [16]

The previous table, as devised by the ministry and TSO, leads in the development of some assumptions. First of all, aiming at the adequacy of the system, there are five factors that are known to affect the reliable supply of the demand. These factors are, the development of demand and consumption (which has an increasing trend, as shown in figure 4.12), the availability of power units, the hydraulic situations, the availability of the interconnected systems and the penetration of RES. The stochastic character of these factors can cause changes in the system and create unforeseen situations. The next figure (4.12) presents the capacity of the power plants, juxtaposed with the peak load for the time period 2017-2027.

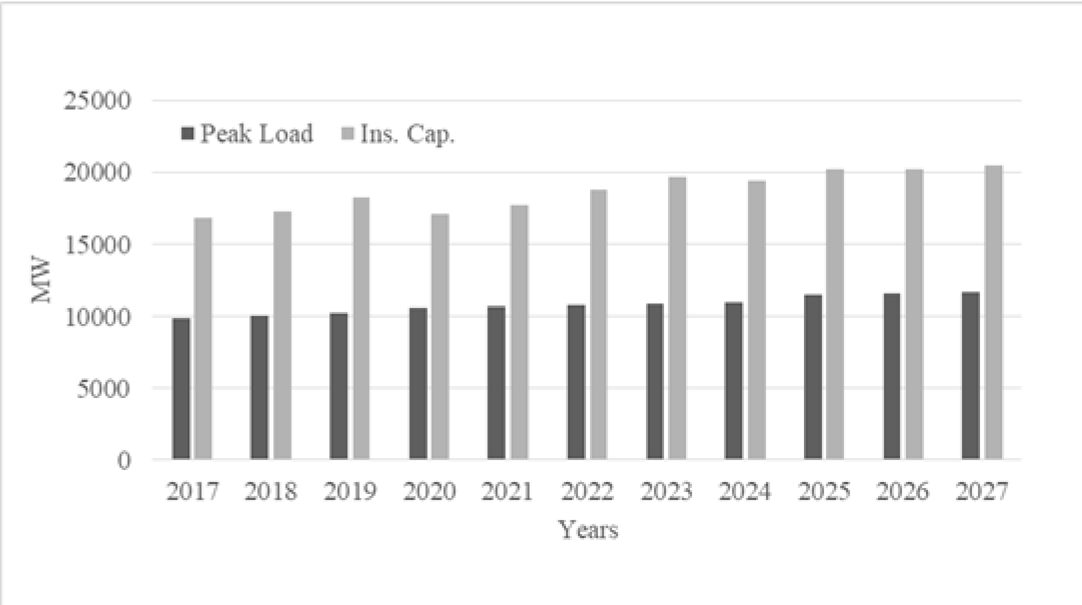


Figure 4.12: Currently peak load & installed capacity in Greece 2017-2027[16]

Apparently, the total installed capacity surpasses the peak load, so it becomes clear that the needs are fulfilled. For this realistc illustration of the system, it was considered that the natural gas production was decreased by 10% in order to avoid wrong forecasting and unexpected problems in the system. The problem is that, from 2025 onwards, a lot of units of PPC will be decommissioned ; the first ones to be decommisioned will be two natural gas units with capacity around 750MW. That will create problems in the to-tal installed capacity, while, at the same time it can be observed that the peak load will have an increasing trend.

4.3.2 Fuel market forecast

Greece, as mentioned before, except for its lignite mines, does not depend on fossil fuels for energy production. That can be problematic in that it rises expenses for the government and for private investors to produce electricity, while leading to an increase in the electricity consumption prices too. The following growth rates are assumptions which be made for more realistic view of the model. Table 4.4 shows the current prices of fuels used in the Greek electricity sector for production purposes (HFO and Diesel, Natural Gas, biomass and lignite), as well as their lower heating values and their growth rate factors which are included in Vuorinen's Planning of optimal Power Systems [42].

Fuel	**Fuel Price**	**LHV**	**Growth %**
	Value per Unit	Value per unit	
Lignite	59.9 €/MWh	5922 MWh/t	1.9
Natural Gas	37 €/MWh	0,010 MWh/t	2.6
HFO	31 €/MWh	11.861 MWh/t	2.9
Biomass	14 €/MWh	5,5 MWh/t	2.6

Table 4.4: Different characteristics of fuels [24,43,44,45,58]

Fuel prices are calculated according to the spatial multi-period long-term planning model of the Greek electricity system [43], LHV was found on biofuels.gr [45] and all the oth-ers were found on the Heinrich Boll Stiftung Institute lignite study [25]. Then, growth rate was found on Vuorinen's Planning of Optimal Power Systems [44]. Prices of fossil fuels are quite low but forecasts predict an upcoming price increase [46]. This assump-tion applies to other fossil fuels as well, even though there is no available data for the Greek market. The fact that oil is one of the key import fuels for Greece, a fuel that de-termines world market prices, presents a valid case for the future of the Greek fuel mar-ket. This development of fuel prices in Greece can be shown in figure 4.13, where the expected fuel price developments for the time period from 2012 to 2030 are presented.

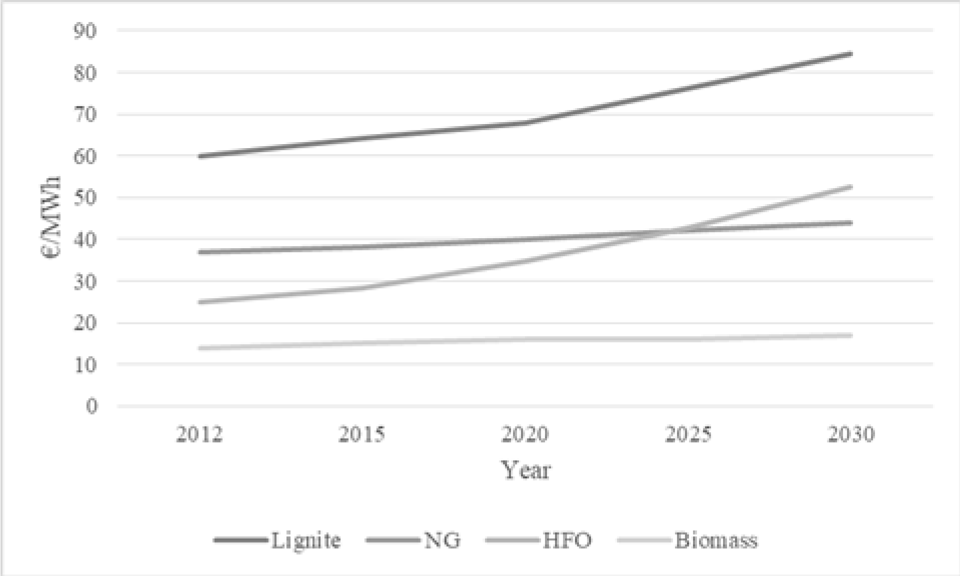


Figure 4.13: Development of fuel price of Greek energy system mix [24,43,44]

4.3.3 Expected development of Capital Expenditures

Nowadays, the investment cost of RES technologies has decreased due to their constant technological progress and the emergence of incentives for their development. Solar and wind power systems are in a more favorable position, concerning the lowest capital expenditures (the forecast of which moves in the same direction), compared to all other technologies, since these find themselves in situation where the clear net cost is very difficult to decrease.

The next table shows the CAPEX and the percentage rates of cost reduction, as expressed in the World Energy Outlook report of 2016, by the International Energy Agency [1].

Tech.	Capital Expenditures	Cost Develop. Rates (%)			
	Value	Measure Unit	2020	2030	2040
COAL	1530	€/KW	0	0	0
OCGT-GT	450		0	0	0
CCGT	900		0	0	0
CHP	1170		0	0	0
ICE (HFO/DIESEL)	500		0	0	0
HYDRO	2385		0	0	0
WIND	1656		3.2	3.3	2.3
PV	1188		21	17.3	9.3
BIOMASS	2160		2.08	2.12	2.17

Table 4.5: CAPEX for all the available technologies of Greece [47,22]

As it can be observed in the entire development, time costs vary according to their corresponding technology. The biggest reduction of cost over time occurs in the case of photovoltaic installations, due to constant improvement and research in that field, with the second most effective technology to reduce costs over time being the wind, which maintains more stable reduction rates.

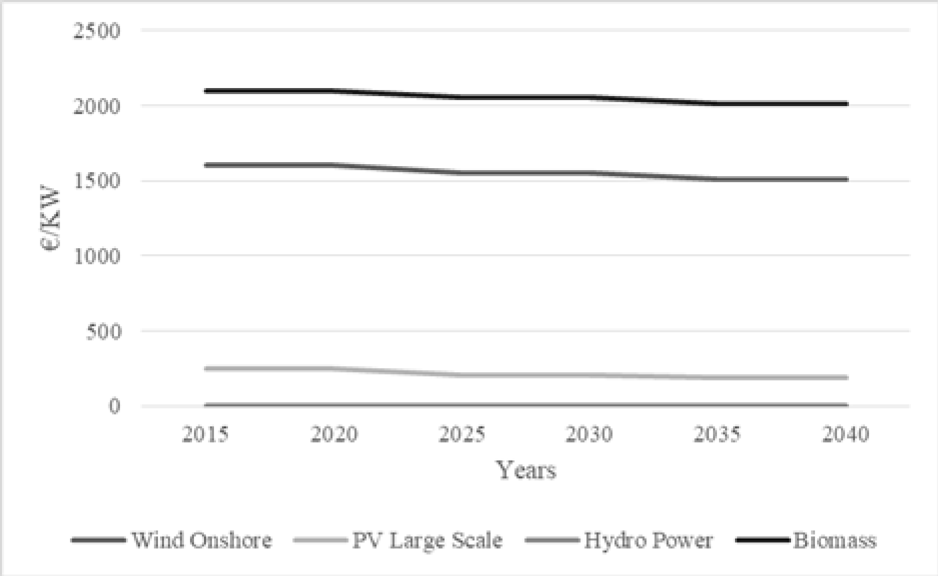


Figure 4.14: Price evolution of RES power generation in Europe [49]

As it can be clearly observed from the figure above, the total investment cost for all RES power units will be reduced during the next years and it will approach the investment cost of a conventional system power plants (in the same scale of capacity) [47]. Of course, according to the 2016 World Energy Outlook, there are other RES technologies with a higher rate of cost reduction, such as CSP, but these are not taken into account in the present study, due to the small number of relevant installations in Greece and the lack of data about future investments.

4.3.4 Load and demand exemplars

In every power generation system there is a percentage of capacity which is regarded as base load for system purposes and which is not subject to change. This is in fact the minimum load the system usually needs for a specific time period, due to the fact that this percentage is usually provided by base fuel power plants. All the other loads are designated as medium and peak loads. Medium load shapes the range of the daily load curve, with the biggest spikes standing for the peak load of the system which is covered from the peak load units. Figure 4.15 shows the daily load curve for a random January day in Greece, according to the power adequacy study 2017-2027 [16].

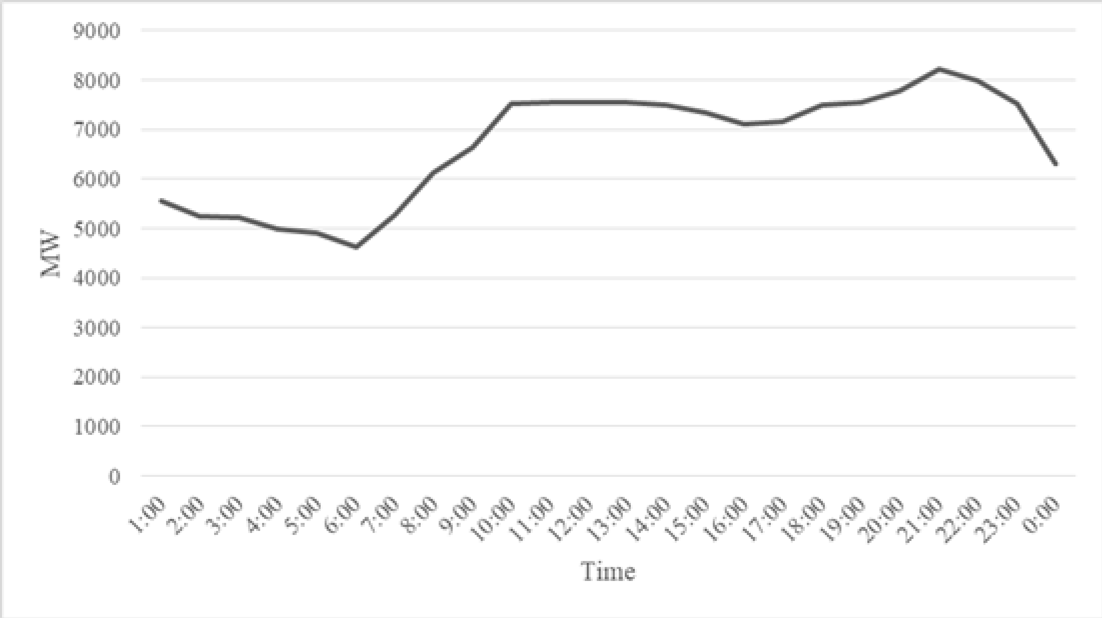


Figure 4.15: Daily load curve for January 2013 [16]

The figure illustrates the base load for the hours after midnight, which is kept in regular levels due to the low consumption of electricity. As it is clear, the biggest amounts can be found at 10:00 and 22:00 with a peak of 8350MW, because during that time the consumption of electricity is increased for heating purposes and for daily activities.

Because the resolution time of the model is Δt=1a, hourly load curves are not integrated in the simulation. Instead, every power plant in general is considered as a load number because there are no restrictions in the production of base or medium load.

4.3.5 Capacity Factor of RES

RES is a unique case. For this study, load will be covered by the thermal power plants due to the fact that RES does not have constant power output. But RES are dispatched always first at the system produced in that way low cost energy. In times of increased solar irradiation and increased demand, photovoltaics replace the medium load thermal units but constant supply cannot be guaranted without storage. The exact same thing happens with wind energy where turbines can produce only a fraction of their capacity to the constant demand. According to weather conditions we can determine the Capacity factor of RES which illustrates the annual use of RES to the system despite their fluctuating character [48]. The following figure presents the average capacity factor and the annual FLH of RES technology, and it proves the necessity of its determination in order to achieve a better performance of the system.

TECH.	CF (%)	ANNUAL FLH (H)
PV	0.46	4027.6
WIND	0.245	2277.6

Table 4.6: Capacity factors and full load hours for PV and Wind technologies [49,22]

4.3.6 Financial Parameters for Energy Technologies

In the following table lie all the investment and operational costs for all the technologies. The interest rate for capital expenses will be 4.5% for reasons of accuracy, due to their fluctuating character. The average data according to ECB is 4.5% [47]. The data from table 4.7 remains stable in all scenarios.

Tech.	Capital Expenditures €/kW				O&M Costs €/kW			
	2015	**2020**	**2030**	**2040**	**2015**	**2020**	**2030**	**2040**
COAL	1530	1530	1530	1530	40.5	40.5	40.5	40.5
OCGT-GT	450	450	450	450	18	18	18	18
CCGT	900	900	900	900	22.5	22.5	22.5	22.5
CHP	1170	1170	1170	1170	36	36	36	36
ICE (HFO/DIESEL)	500	500	500	500	18	18	18	18
HYDRO	2385	2385	2385	2385	72	72	72	72
WIND	1656	1602	1548	1512	41.4	39.6	39.6	39.6
PV	1188	936	774	702	12.6	10.8	10.8	10.8
BIOMASS	2160	2115	2070	2025	76.5	72	72	72

Table 4.7: Financial parameters of available technologies [47,59]

4.4 Scenarios

At this section are presented the scenarios that will be assessed at following chapter.

4.4.1 Base case scenario

Base case scenario is the representation of the least cost system expansion. The initial point of it is the existing situation of the electricity system with the already contracted units. In this scenario applied the goals of national energy roadmap of 2050.

Optimization period is from 2015 to 2040 and the interest rate is 4.5% as it is mentioned before. The available technologies are the existing technologies without the use of CSP and geothermal power units and biomass. The decrease in the lignite use, the elimination of use of diesel and HFO and the increase of natural gas at the percentage of 45% are studied. Also the target for RES is pointed at the 18% according to the goals of EU.

4.4.2 Increase self-independency

The next scenario searching the possibilities of increasing the self-independency of the Greek power system. That means the elimination of the imports and the production of energy from non-local resources with a direction to RES. For this scenario will be implemented the target of 18% from RES, the extension of lifetime of lignite units through the FLH of lignite plants and the stabilize of natural gas plants at the levels of 2015.

All the available technologies are included and also the growth rate of import fuels (natural gas) set at 20%. Again the extension of diesel and HFO considered as zero with the lack of the capacity for these fuels to covered by RES and especially Wind turbines and PV’s.

4.4.3 Increase of RES share at 20%

The latest scenario has a lot of commons with the base case scenario. Optimization period is until 2040 and the interest rate is 4.5% as it is mentioned at the first scenario.

The constant decommision of old lignite units and also the integration of some new according to the investments that have all ready set, the elimination of use of diesel and HFO and the increase of natural gas at the percentage of 45% are studied. Also the target for RES is pointed at the 20% in this scenario according to revised goals of Greek authorities. In the following table are represented all the necessary data for the three scenarios.

5 Optimization results of the scenarios

In this chapter are presented the scenarios that the author chnoose for the study of Greek electricity System.

5.1 Scenarios

This section provides the result of the implemented scenarios that made by the author. The first scenario has to do with the targets that Greek authorities have imposed for the next years according to the targets of Roadmap 2050. The assumptions have been made for simplicity reasons and more accurate results. The second has to do with the expansion of generation plan according to the increase of self-efficiency to the energy mix of the country. Lastly, the third scenario is the bigger integration of RES into the system until the percentage of 20%. All the three scenarios have the same structure which is the presentation of the nominal capacity of the mix, the RES percentage of the mix and finally the CO_2 emission savings. The assessment of these three scenarios based on the cost analysis according to OPEX and CAPEX.

5.1.1 Base case scenario

The present scenario based on the Roadmap of 2050 and in targets which has Greek government establish .

Energy mix of the country

First at this scenario presented the reduction of the stock capacity through the years figure (5.1). The nominal capacity of the energy mix of the country presented in the figure (5.2) for 25 years which is the total time of our simulation.

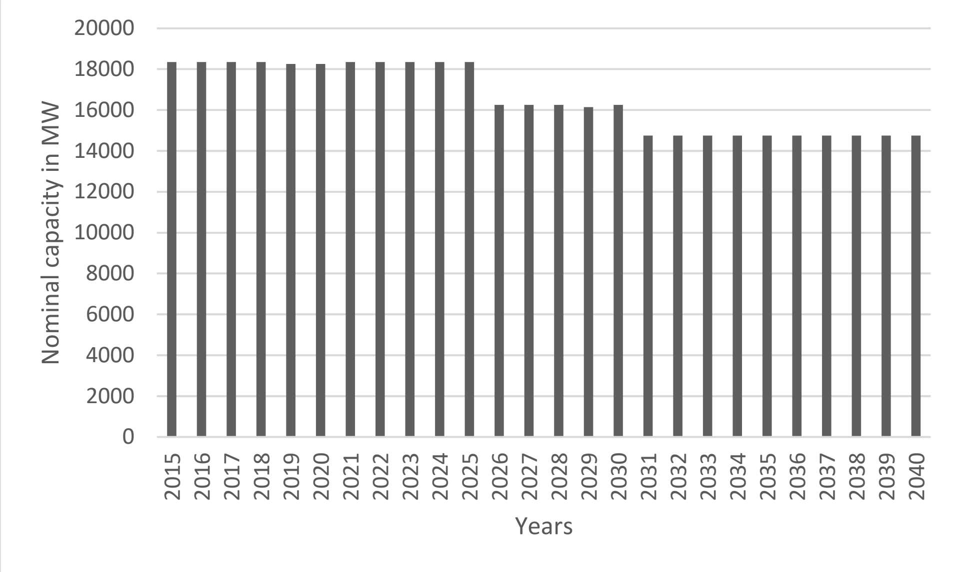


Figure 5.1: Reduction of stock capacity of plants

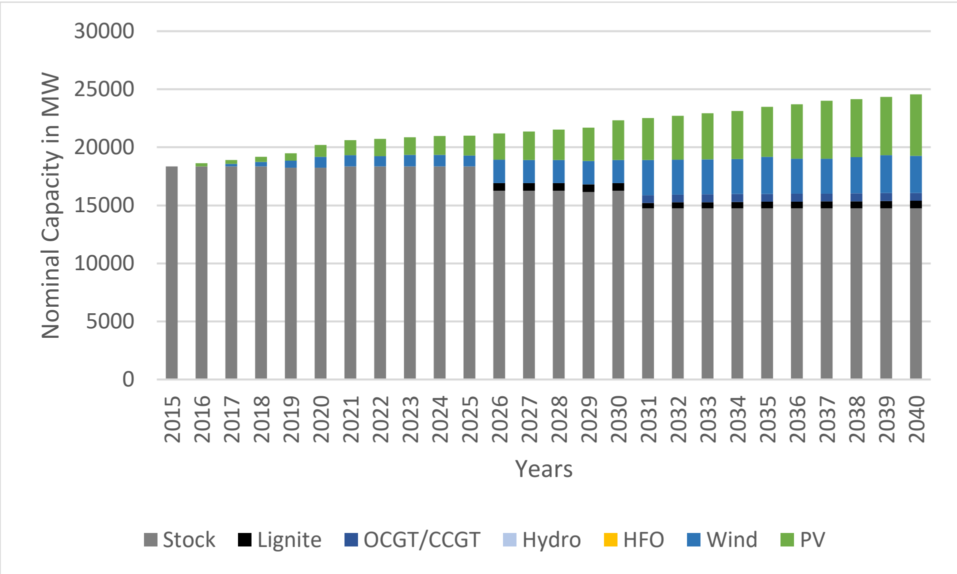


Figure 5.2: Nominal capacity of base case scenario

The stock power plants are presented in the figure 5.2 as have already described in the chapter 4 and illustrated with grey color. For the first 5 years the nominal capacity is from 18239 MW until 20025 MW at 2020. Taking into consideration the 15% of reserve peak demand that have imposed and also taking into consideration the table 4.3 with the forecast of demand, the system seems stable to the changes, with enough installed capacity to cover all the needs. Until the year 2023 the system does not take into consideration any decommission of any unit and any commission of them. The first decommission of units happen at then year 2023 with total withdrawal of the system 3800MW. The model at this time shows also a stability by suggesting the rise of the RES in the system by the installation of 3178 MW. The peak reserve of 15% allow to the system the decommisioning of these units. Due to the fact that RES penetrated first into the system and also the decommissioned 1800MW are base load (lignite units) the model suggest the installation of 600MW of lignite production. That seems right due to the fact that the total demand at this year (according also to ADMIE study) the demand increase. The rise in the percentage of RES is small due to the fact that lignite production has the leadership in the production. In addition this small rise coming as a result of the targets that Greek government has imposed for 2020. The next big differentiation in the percentages is illustrated at the year 2025. At this year in order to cover the total demand the model also suggest the integration of more RES power into the system at the levels of 9000MW. The integration also of a new lignite unit seems necessary in order to cover the demand for the base load. The unit of Ptolemaida 5 (660MW) is integrated to the model and also gives the security supply in the system. The annual load demand also cover in this scenario. Due to the fact that no other expansion plans for lignite production the change on the FLH (which occurred manual for every year) seems necessary in order to cover the demand. As the nominal capacity developed the with first role at the Windpower and PV systems, with the reduction of the stock capacity at the same time, the integration of CCGT units seems necessary due to their low cost and the instant offer to the system. That means that the capacity of the corresponding lignite power plants should be replaced with a combined cycle plant. That also give an energy safety advantage for Greece which is a country with no fuel production because the focus in production of electricity out of just one main kind of technology has tremendous risks and instabilities. In addition, integration of a new power plant with rapid electricity generation reactions give the safety of the provision of electricity in times of fluctuations of peak loads. That’s why from the year 2030 is proposed a constant investment in NG power plants and also a change in FLH to cover all these needs. Lastly, the fluctuation at the nominal capacity and especially at the stock production from the year 2035 until the end comes from the possible decommissioning of units (Heron 1,2,3 – GT units) and also from the changes in FLH. On the other hand, the security mix is ensured by the integration of RES in the system which has a full field of use as well as the convenient ground for further development in Greece. The table (5.1) demonstrate the renewable energy share of the mix at the base case scenario.

	2015	2020	2025	2030	2035	2040
Wind Power	8.5	11,9	15	18,45	19,5	20.85
PV	7.3	8,96	14,2	17,69	19,2	20,89
Total share	15,8	20,86	29,2	36,14	38,7	41.47
RES target		18%				40%

Table 5.1: Renewable energy share for the base case scenario

Since Greece is has a bigger advantage of wind power installations the model primary builds this type of technology. Besides, solar power is very competitive with thermal power plants and is therefore integrated in the system in bigger percentages after 2025. As it is mentioned from the table 5.1 and from the figure 5.2 the renewable energy sources occupied a great amount of energy production in the system. In addition the targets that Greek government imposed for until these years seems to be achieved (with the new and also the stock installations) and in some cases like 2020 to be overpassed with more than 6400MW at 2020.

CO2 Emissions

One other very important issue is the minimization of CO_2 emissions. The present model calculates the emissions every year and it as it is seems the total reduction of the emissions is possible. The total sum of emitted carbon dioxide over the entire planning horizon of 25 years reduced from 37000 kt to 18670 kt of CO2 with a total energy production of 62695 GWh. As all power plants in 2015 are assumed to have specific FLH and specific fuel, with the majority of them natural gas in nominal power instead of lignite with a high emission factor, it presumed that the calculated value is probably under the real amount. The calculation based on assumed FLH, with the voidness of the environmental assessment of the scenarios based on this value. Since the quantity of emissions depends on the efficiency and the used fuel type, two different options are defined in order to show the range in which the reductions have been estimated. The first, a CCGT plant with an efficiency approximately of 48%. Because natural gas has a low emission factor in accordance with lignite units which have a high emission factor, the amount of carbon, which this plants produces with the same megawatt hours as the renewables, indicates a very prominent value. Secondly, a conservative valuation is estimated by taking a lignite plant, as the combined cycle plants functions is on a relatively lower efficiency and the combustion of lignite is characterised by a high emission factor. The results of this analysis illustrates Figure (5.3).

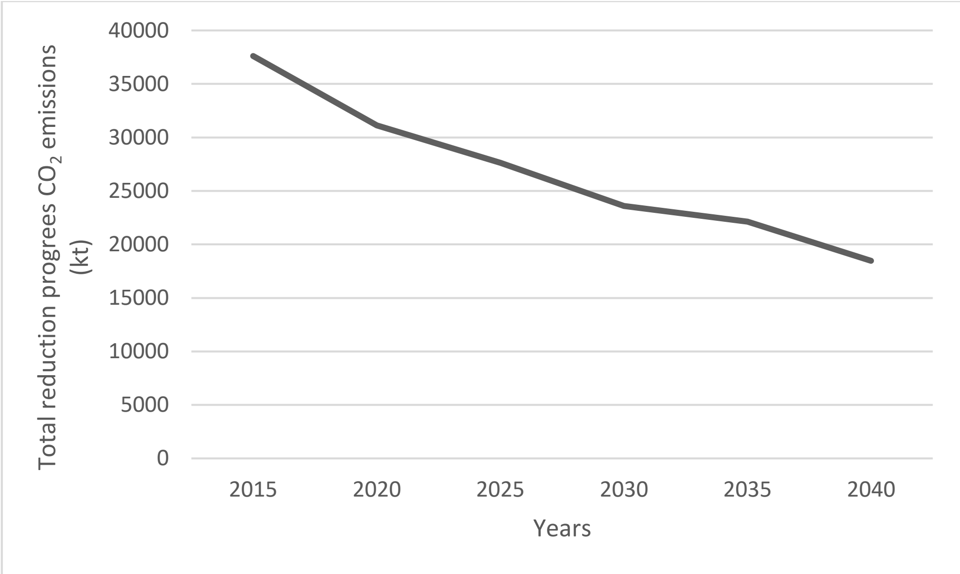


Figure 5.3: Total reduction progress of CO_2 emissions for 25 years of simulation

As illustrated in the previous figure, the reduction amount of CO_2 emissions is increased every year with a most increased values after 2020 and the big boost of RES in the system. The total amount of emissions at 2040 is less than 20000 kt which is a very prominent value a very realistic if it considers the share of RES in the system at this time.

5.1.2 Increase of self-independency

Due to the fluctuating character of RES and also the fluctuating values of fossil fuels and especially natural gas the scond scenario incorporates the increase of the self-efficiency of the system by the extension in life years of lignite power plants and also the non-investments in the natural gas power plants. RES also play a significant role in the system but has a secondary place.

Energy mix of the country

The next figure (5.4) presents the total amount of nominal capacity into the system until 2040. The difference between the first and the second scenario permits a new description for the following case.

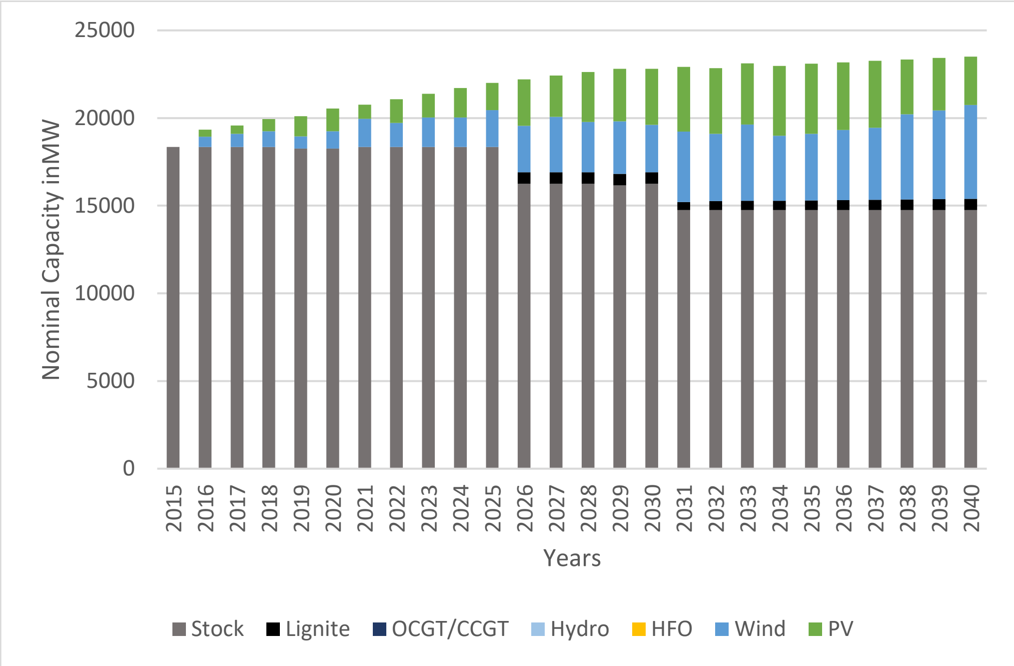


Figure 5.4: Nominal capacity of power plants for increase self-efficiency scenario

The first difference between the previous scenario is that the model does not suggest any natural gas plant. For this change the charge goes to the fact that the most of the lignite units take an extension to their life. At the end of 2025 only the lignite units of Amynteon and Kardia decommissioned from the system. At these years the biggest increase is for RES units. In addition, one other assumption that it does not took participation is that the hydropower stays stable which means that Ilarionas power plant does not take participation of the system. Lastly after the year of 2030 only the units of Agios Dimitrios goes out of the system and at the same time for the reason of stability of the system observed an increase in the FLH of lignite plants. After 2026 only 2 units of lignite commissioned into the system and these are Ptolemaida V and Meliti II. All natural gas plants participate at the system without no change in their production. The model propose the rise of the capacity only with RES in order to achieve the goal of RES which remain stable from the previous scenario and it is 18% until 2020. As it is clearly mentioned the goal that Greek government and EU have imposed for the Greek situation is marginally achived but for 2040 this case scenario fails. The next table (5.2) showns this percentage difference.

	2015	2020	2025	2030	2035	2040
Wind Power	8.5	8.87	11.59	16,11	18.35	20.5
PV	7.3	9,64	13.65	15.34	17	19,44
Total share	15,8	18.5	25.24	31.45	35.35	39.9
RES target		18%				40%

Table 5.2: Renewable energy share for the self-efficiency scenario

As it is clearly observed in this scenario the although it is observed an increase in RES the percentage are less than the previous. The RES occupied a big amount but the use of lignite plant, the commision of new plants and the stable situation in the natural gas units stay the percentages in low rates.

CO2 Emissions

The total CO_2 emission are presented in the following figure (5.5).

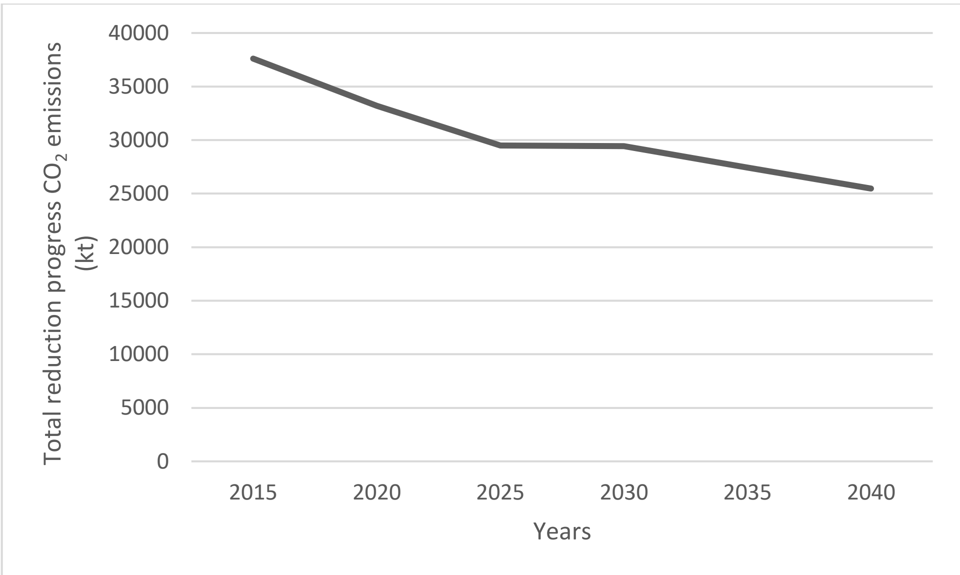


Figure 5.5: Total reduction of CO_2 emissions for the self-efficiency scenario

As it is clearly observed the total amount of CO_2 emissions have also a decrease but smaller to the first scenario. The main impact in these values is from the constant use of lignite plants and the small amount of RES installation instead with the previous scenario. In this scenario the total amount decrease at 25000 kt of CO_2 with a constant reduction at the years 2015-2025 because of RES installation, and 2025-2040 due to the decommission of the units and also again the installation of RES.

5.1.3 Increase of RES share

The next scenario present the rise on the energy share of the renewable targets. The goal from 18% rises at 20% at 2020.

Energy mix - RE-share to 20%

The rise of the goal of RES according to the roadmap of 2050, at 20% illustrated in the next figure (5.6).

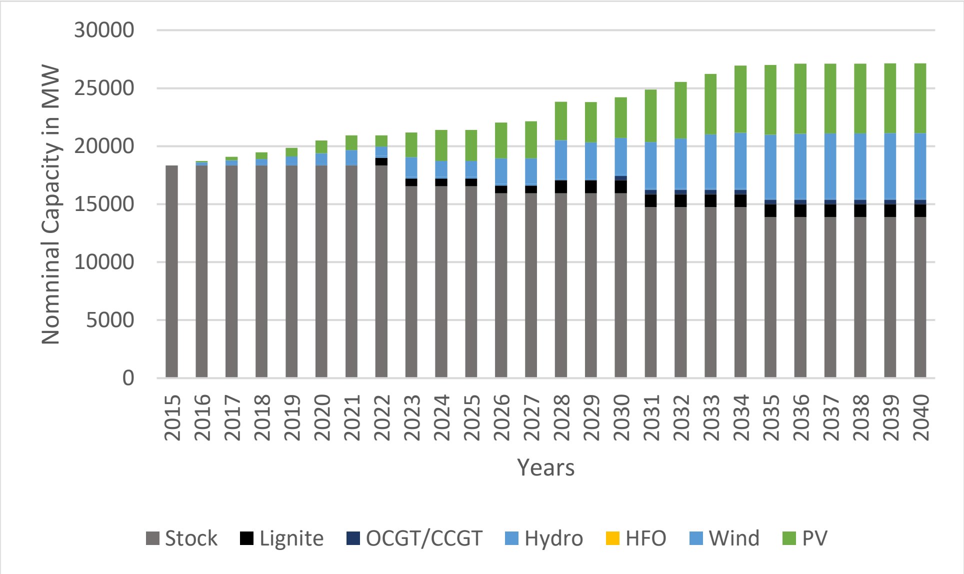


Figure 5.6: Nominal capacity of power plants for increase of RES goal at 20%

At this scenario, is followed the same methodology as the first scenario. The first thing that ins mentioned is the rise in the total energy mix. The induction and decommission of the units are the same except the stock natural gas units which stay at the model, is one of the factors that influence. These natural gas units stay at the model due to the fact that they does not exist a plan of decommission. At the first scenario this units decommissioned with the assumption that the their total life is approximately 30 years. The only thing that changed is the percentage of RES goal to 20%. During the whole procedure solar power is used with bigger percentage as the model suggest to achieve the given renewable energy targets, until the year 2031 which came approsimately at the same level with wind power. This fact indicates that solar power has the least cost till this year out of the two desired renewable technologies. The share of renewables as contribution to the total demand is illustrated in Table (5.3).

	2015	2020	2025	2030	2035	2040
Wind Power	8.5	9.86	13.61	18,21	20.78	22.76
PV	7.3	10.83	14.85	19.78	22.8	24.98
Total share	15,8	20.69	28.46	37.99	43.58	47.47
RES target		20%				40%

Table 5.3: Renewable energy share for the self-efficiency scenario

As it easily observed in this scenario all the targets are fulfilled. At 2020 the percentage is 20.69% in the mix (with the stock existing units of RES) and at the end of the 2040 this percentage is 7.47% more than the target, which is a very prominent scenario for the future.

CO2 Emissions

The total CO_2 emission are presented in the following figure (5.7).

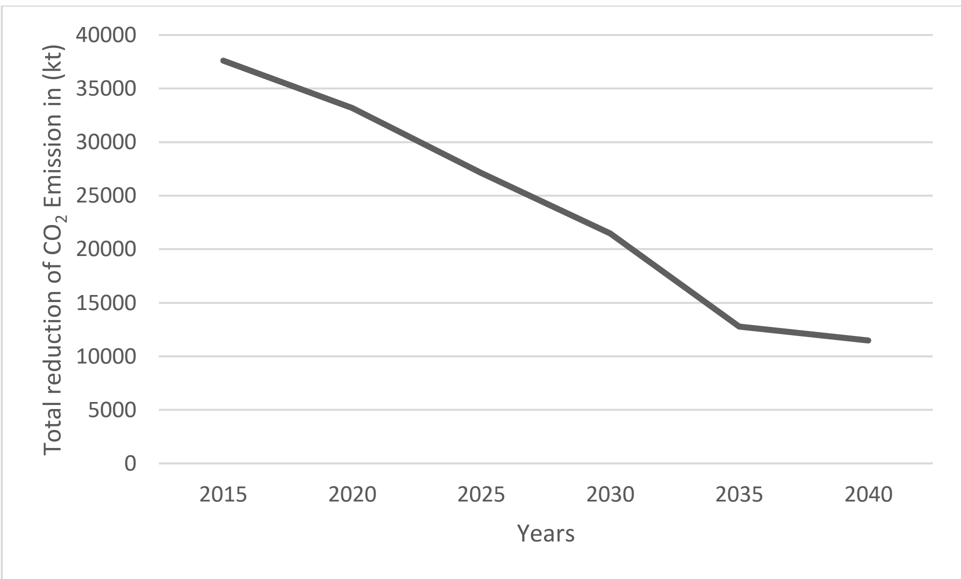


Figure 5.7: Total reduction of CO_2 emissions for the RES – share 20% scenario

This scenario is characterized by a constant expansion of renewable technologies. The rise in the percentage give a bigger amount of reduction in CO_2 emissions. The 37610 kt of CO_2 at 2015 reach the 11476 kt CO_2 at the end of 2040. This great reduction is gives at this scenario the first position accordnig with the other. This is normal due to the induction of more RES and also the use of CCGT units instead of lignite units. Although, the nominal capacity rises in bigger amount the use of more RES causes a bigger amount in results of CO_2.

5.2 Assessment

The following assessemt based in the costs of the model. The first figure 5.8 is the total amount of CAPEX for the three scenarios.

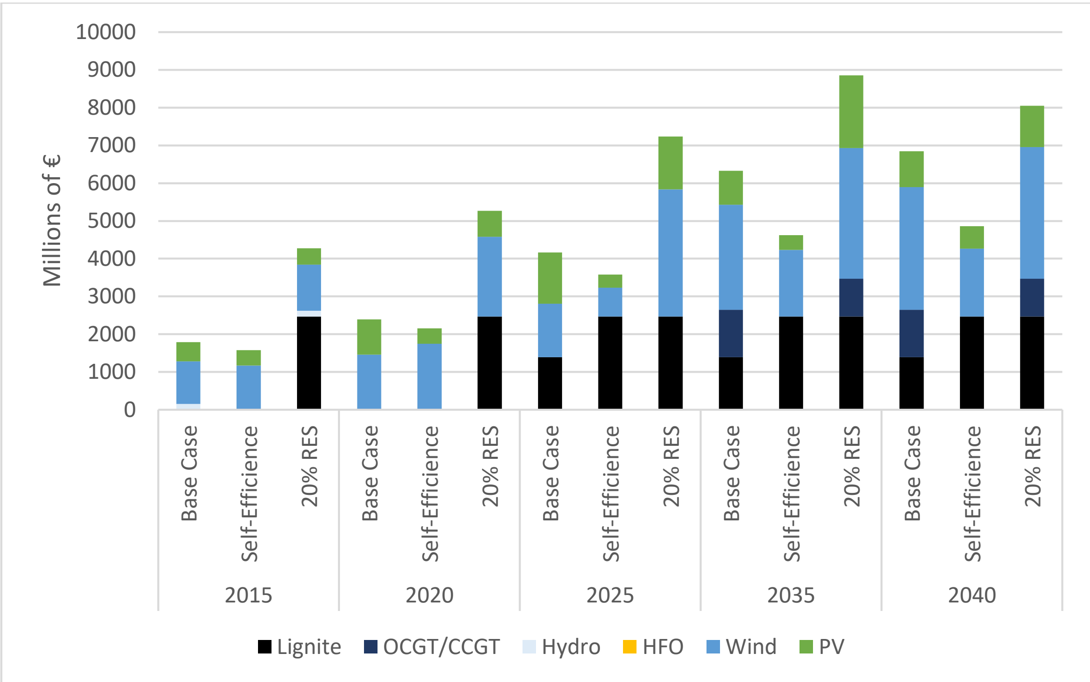


Figure 5.8: Average capex in million of €

For the three cases the assessment scenarios reach the targets that have been imposed are fulfilled. At the base case scenario the amount of 1,9 billion € is the starting amount for the years 2015-2020 which is needed in order to cover the demand and also to cover the targets that have been imposed. At the other two scenarios the investment costs of RES ave bigger amount than the base case scenario due to the nature of their study. As it is clearly observed the costs for all the scenarios reaches the amount of approximately 9 billion € which is very prominent value if it considers the investment costs of lignite and natural gas plants which is very high (years 2035-2040), in accordance at the same time the investments of RES which also occupied with higher nominal capacity.

In the other hand the calculate OPEX for these scenarios in illustrated at the figure 5.8. In this figure it should be mentioned that the base case scenario is the main scenario of that it should be considered as the most realistic solution. Since the demand is increasing, new plants need to be built and therefore the OPEX increases too.

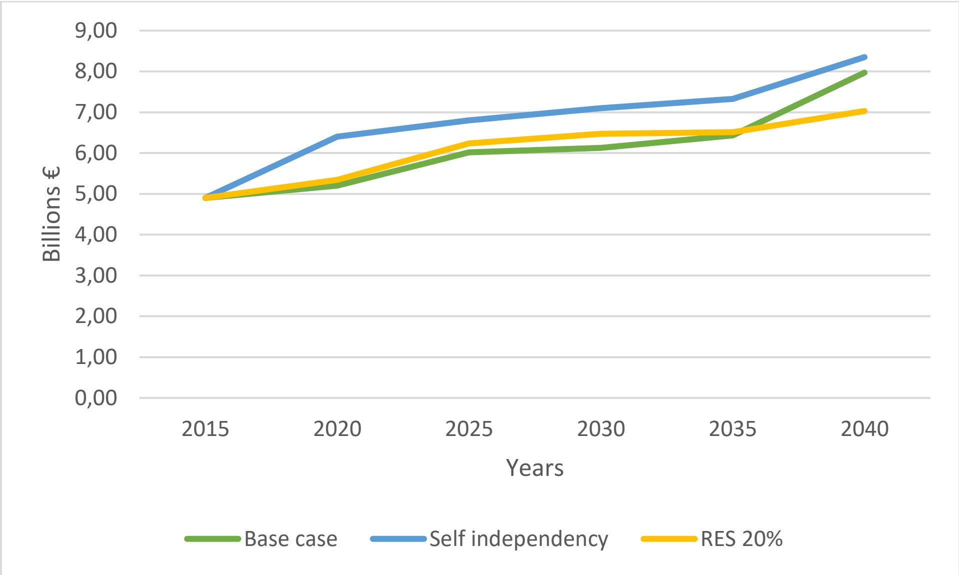


Figure 5.9: Development of the OPEX for selected scenarios

The graph plots the total OPEX of the different scenarios, which is estimated through the nominal capacity and the FLH. The cost functions should depict an incline instead of a calculation of the specific values. The total OPEX increases because of the rise of the carbon credit costs and authors assumptions. Further, a reduction of the OPEX is noticed while meeting the renewable energy target of 18% till 2020. In conclusion, due to the assumed increase of fuel costs the OPEX of a capacity expansion plan increases.

The CAPEX for the ‘’base case” scenario estimated around 6935 million € for the entire planning horizon of 25 years from 2015 till 2040. For the rest of the scenario no further data are given so an adequate comparison is not possible. The comparison of the results of the scenarios are integrated according to the ADMIE completed capacity expansion plan for Greece [19].

6 Conclusions

At the present thesis was held the development of long-term optimization plan for the Greek electricity system. The subject was the least-cost optimization approach and at the same time the expansion of the system with adequate integration of RES. The optimization problem was transformed into a model in order to solve it via linear programming. As it was prerequisite for the assumption of the thesis, the theoretical and mathematical background for the use of the model was necessary in order to described and implement all the necessary mathematical functions for the extraction of the results. The description of the model was given with all the documentation of the applied methodology. Parameters of the model like input data, objective functions, constraints and boundaries was included to the model. For the long term integration, according to the time step method the resolution time was defined $\Delta t=1\alpha$ for the 25 years of the optimization study. For the first stages they used average annual inputs such as nominal capacities, econnimic data, characteristics of the system and at the second the outcomes which used to the simulation in order to extract the results for the costs and the total capacity of the system for the implemented scenarios. All the methodology was implemented in Microsoft Excel software and solved with the Solver add-in for Greece case study with all the parameters of the country energy system. In that part is important to mention that the use of some data made by assumption due to the lack of them.

For the case study of Greece all the data came from the official authorities, with the majority of them from ADMIE and the scenarios of authors choice based in the future plans that Greek government state. The development of the demand and also the total costs are studied in order to create a better future scenario for the system. The meet of the national targets and the optimization of the factors of cost (as it is presented in the assessment) and demand was fulfilled in the three scenarios.

The results gave the general opinion that the Greek electricity system can penetrate more than 18% of RES to the system which is the European target that imposed for 2020. Following the same steps the target of 20% which government has state is also possible as it was presented in the third scenario. Of course, the mix can not state only with RES but also with the combination of natural gas and lignite units, taking into consideration the costs of this units especially in the financial and economical crisis that Greece face at this time.

Furthermore, the expensive and pollutant coal it reaches a quagmire due to the fact that all the implemented policies are talking about reduction in power generation from lignite, except from the already investments that has be done (Ptolemaida V). In addition, Greece should find another ways to produce energy due to the fact that base fuel starts to be very expensive.

Before the end, the present model can developed more according to the needs of each study and can give the chance to develop further more accurate scenarios of the choice of every researcher. The variation of the fuel price according to the use of fuels in energy system as well the change of the resolution time are some of future development scenarios. Owning to the high investment costs, a more considered plan has to be applied. In order the results should agree with the research further scenarios should be examined under some assumptions. A very interesting scenario would be the variation of different fuel types. The model permits to create the optimum capacity with different input data. For further investigation according to the feasibility of the operation plan the results should be further examined via an operation analysis. It is important to develop a new model for the operation analysis, not to use Excel because the obtained results are from that program. The developed model itself could be extended by inserting more potential new power plant options or various further constraints.

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Appendix

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Lignite	0	0	0	0	0	0	0	0	0	0	0	660
OCGT/CCG	0	0	0	0	0	0	0	0	0	0	0	0
Hydro	0	0	0	0	0	0	0	0	0	0	0	0
HFO	0	0	0	0	0	0	0	0	0	0	0	0
Wind	0	0	233	383	589	944	967	891	1001	1008	932	2020
PV	0	276	322	456	638	1000	1289	1489	1503	1622	1732	2253
Stock	18351	18351	18351	18351	18251	18251	18351	18351	18351	18351	18351	16251
Total	18351	18626,27	18905,66	19189,24	19477,08	20484	20606,9	20730,55	20854,93	20980,06	21015	21183,12
Lignite	0	0	0	0	0	0	0	0	0	0	0	660
OCGT/CCG	0	0	0	0	0	0	0	0	0	0	0	0
Hydro	0	0	0	0	0	0	0	0	0	0	0	0
HFO	0	0	0	0	0	0	0	0	0	0	0	0
Wind	0	580	750	900	695	1000	1600	1369	1680	1677	2110	2649
PV	0	399	483	690	1156	1300	806	1350	1354	1677	1539	2649
Stock	18351	18351	18351	18351	18251	18251	18351	18351	18351	18351	18351	16251
	Base Case	Self-Efficien	20% RES	Base Case	Self-Efficien	20% RES	Base Case	Self-Efficien	20% RES	Base Case	Self-Efficien	20% RES
Lignite	0	0	2467	0	0	2467	1389	2467	2467	1389	2467	2467
OCGT/CCG	0	0	0	0	0	0	0	0	0	1255	0	1003
Hydro	150	0	150	0	0	0	0	0	0	0	0	0
HFO	0	0	0	0	0	0	0	0	0	0	0	0
Wind	1134	1167	1223	1458	1750	2112	1420	763	3370	2788	1764	3463
PV	508	408	439	935	408	689	1352	353	1400	894	394	1923
	2015	2015	2015	2015	2015	2015	2015	2015	2015	2015	2015	2015
	Base Case	**Self-Efficier**	**20% RES**	**Base Case**	**Self-Efficier**	**20% RES**	**Base Case**	**Self-Efficier**	**20% RES**	**Base Case**	**Self-Efficier**	**20% RES**
Lignite	22125	22125	36875	17997	23996	17997	16454	27423,33	27423,33	13699	18265,33	22831,67
OCGT/CCG	11902	15869,33	15869,33	13708	22846,67	22846,67	14976	14976	24960	14502	24170	24170
Hydro	5501	7334,667	5501	5820	5820	7760	5904	9840	5904	6176	8234,667	6176
HFO	3788	5050,667	3788	3555	5925	4740	1996	2661,333	1996	843	1124	1405
Wind	4765	4765	4765	5557	9261,667	5557	8417	11222,67	14028,33	11458	11458	19096,67
PV	4862	4862	6482,667	4751	6334,667	6334,667	6210	6210	10350	7108	9477,333	11846,67

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2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
660	660	660	660	450	508,5	523,755	539,4677	555,6517	572,3212	589,4909	607,1756	625,3909
0	0	0	0	680	680	680	680	680	680	680	680	680
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
2000	2000	2000	2000	3035	3000	3010	3024	3187	3018	3000	3106	3252
2442	2613	2885	3404	3600	3779	3958	4135	4325	4689	4980	4994	5047
16251	16251	16151	16251	14751	14751	14751	14751	14751	14751	14751	14751	14751
21352,58	21523,41	21695,59	22315	22515,84	22718,48	22922,94	23129,25	23499	23710,49	23923,89	24139,2	24356,45
660	660	660	660	450	508,5	523,755	539,4677	555,6517	572,3212	589,4909	607,1756	625,3909
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
3150	2861	2999	2700	4020	3839	4352	3698	4174	3999	4115	4850	5049
3049	2700	2999	3200	3700	3739	3500	3985	4174	3858	3806	3135	3000
16251	16251	16151	16251	14751	14751	14751	14751	14751	14751	14751	14751	14751
Base Case	Self-Efficien	20% RES	Base Case	Self-Efficien	20% RES	Base Case	Self-Efficien	20% RES	Base Case	Self-Efficien	20% RES	Base Case
1389	2467	2467	0	0	0	5	8,333333	5	742	1236,667	1236,667	0
1255	0	1003	0	0	0	2	2,666667	2,666667	0	0	0	0
0	0	0	0	0	0	15	25	15	0	0	0	695
0	0	0	9	15	12	0	0	0	0	0	0	6
3247	1800	3489	1134	1134	1512	1458	1458	2430	1420	2366,667	1420	2788
950	594	1089	508	508	508	935	1246,667	1246,667	1352	2253,333	1352	894
2015	2015	2015	2015	2015	2015	2015	2015	2015	2015	2015	2015	2015
Base Case	**Self-Efficier**	**20% RES**	**Base Case**	**Self-Efficier**	**20% RES**	**Base Case**	**Self-Efficier**	**20% RES**	**Base Case**	**Self-Efficier**	**20% RES**	**Base Case**
8304	2035	13840	7851	10468	7851	0	0	0	5	8,333333	5	742
17618	8304	29363,33	18571	24761,33	18571	0	0	0	2	2,666667	2,666667	0
6802	17618	6802	6698	11163,33	8930,667	0	0	0	15	25	15	0
751	11336,67	751	704	1173,333	938,6667	9	15	12	0	0	0	0
14008	751	23346,67	16820	28033,33	22426,67	1134	1134	1512	1458	1458	2430	1420
8967	14008	11956	8401		14001,67	508	508	508	935	1246,667	1246,667	1352

Type of plar	Installed Ca	Typical Inst	NUMBER OI	NUMBER OI	Investment	Load Factoı	FLH(h) of or	Discount Rı	Lifecycle (yı	Fix O&M co	VAR O&M c	LHV (MJ/kg
Lignite	4928	300	16,42667	16	1584	0,75	6570	14	40	21653,8	2500	18,85
OCGT/CCGT	4560	450	10,13333	10	880	0,46	4029,6	14	35	8500	3500	50
Hydro	3018	70	43,11429	43	2300	0,37	3241,2	14	30	10715,4	1915	0
HFO	730	100	7,3	7	880	0,46	4029,6	14	30	8284,6	3500	40,2
Wind	1453	20	72,65	73	1350	0,245	2146,2	14	20	23830,9	0	0
PV	724	5	144,8	145	1200	0,3	2628	14	20	9184,6	0	0
Total	15413											
	FLH(h) of or	Discount Rı	Lifecycle (yı	Fix O&M co	VAR O&M c	LHV (MJ/kg	ηel,p (%)	EFFUEL (tCC	EFFUEL (tCC	Ccre(€/tCO	g (growth rı	cFUEL,p=cF
Lignite	6570	14	40	21653,8	2500	18,85	30	0,114	1,14	15	1,9	59,9
OCGT/CCGT	4029,6	14	35	8500	3500	50	45,6	0,056	0,202	15	2,6	50
Hydro	3241,2	14	30	10715,4	1915	0		0	0	0	0	0
HFO	4029,6	14	30	8284,6	3500	40,2	37,5	0,078	0,281	15	2,9	40,2
Wind	2146,2	14	20	23830,9	0	0		0	0	0	0	0
PV	2628	14	20	9184,6	0	0		0	0	0	0	0
Total												
(Decommis	Commissioning of units											
2023 αφαιϱ	2022 προστίθενται 600MW											
2030 αφαιϱ	2025 προστίθενται 450MW											
Load Factoı	Discount Rı	Lifecycle (yı	Fix O&M co	VAR O&M c	LHV (MJ/kg	ηel,p (%)	EFFUEL (tCC	EFFUEL (tCC	Ccre(€/tCO	g (growth rı	cFUEL,p=cF	ri annual lo
0,75	14	40	21653,8	2500	18,85	0,3	0,114	1,14	15	1,9	59,9	0,06
0,46	14	35	8500	3500	50	0,456	0,056	0,202	15	2,6	50	0,06
0,37	14	30	10715,4	1915	0	0	0	0	0	0	0	0,06
0,46	14	30	8284,6	3500	40,2	0,375	0,078	0,281	15	2,9	40,2	0,06
0,245	14	20	23830,9	0	0	0	0	0	0	0	0	0,06
0,3	14	20	9184,6	0	0	0	0	0	0	0	0	0,06
				CONSTRAINTS							FULLFILLEMENT OF ENE	
CONSTRAINTS					CAP. * PLF	μ factor	DEMAND RI	EXPECTED DEMAND				
	CAP. * FLH	μ factor	DEMAND RISE		3600	0,131028	157,2339	180,819				32376960
	2356	0	0		2070							18374976

electricity production

	2015	2020	2025	2030	2035	2040
Lignite	22125	22125	18300	13699	8304	7851
OCGT/CCGT	11902	13708	14976	14502	17618	18571
Hydro	3000	1000	1000	1000	1000	6698
HFO	1800	500	500	500	500	704
Wind	5557	5557	8417	11458	14008	16820
PV	5862	4751	6210	7108	8967	8401
	50246	47641	49403	48267	50397	59045

CAPEX

	2015	2020	2025
Lignite	0	5	742
OCGT/CCGT	0	2	0
Hydro	0	15	0
HFO	9	0	0
Wind	1134	1458	1420
PV	508	935	1352
	1651	2415	3514

electricity production

	2015	2020	2025	2030	2035	2040
Lignite	22125	17997	16454	13699	8304	7851
OCGT/CCGT	11902	13708	14976	14502	17618	18571
Hydro	5501	5820	5904	6176	6802	6698
HFO	3788	3555	1996	843	751	704
Wind	4765	5557	8417	11458	14008	16820
PV	4862	4751	6210	7108	8967	8401
Stock						
Total						

	2015	2016	2017
Lignite	0	0	0
OCGT/CCGT	0	0	0
Hydro	0	0	0
HFO	0	0	0
Wind	0	580	750
PV	0	399	483
Stock	18351	18351	18351
Total 1	18351	18589,56	18831,23
Total		1,3	

Wind Powe
PV
Total share
RES target

2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
660	660	1110	1110	1110	1110	1110	1110	1110	1110	1110	1110	1110
0	0	0	0	380	380	380	380	380	380	380	380	380
150	150	150	150	150	150	150	150	150	150	150	150	150
3096	3186	3314	3504	3516	4518	4892	5221	5789	6007	6018	6018	6018
15951	15951	15951	15951	15951	14751	14751	14751	14751	13891	13891	13891	13891
21984,99	22578,58	23188,21	23814,29	24223	24877,02	25548,7	26238,52	26946,96	27000	27100	27110	27120

CAPEX

	2015			2020			2025		
	BaU	LIG	RES	BaU	LIG	RES	BaU	LIG	RES
Lignite	0	0	0	5	8,333333	5	742	1236,667	1236,667
OCGT/CCGT	0	0	0	2	2,666667	2,666667	0	0	0
Hydro	0	0	0	15	25	15	0	0	0
HFO	9	15	12	0	0	0	0	0	0
Wind	1134	1134	1512	1458	1458	2430	1420	2366,667	1420
PV	508	508	508	935	1246,667	1246,667	1352	2253,333	1352